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HOT SURFACE IGNITION TESTS OF AIRCRAFT FLUIDS

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AIR FORCE SYSTEMS COMMAND
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NOTICE

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Five fluids commonly found in aircraft engine components, JP-4 and JP-8 fuels, Mil-H-5606 and Mil-H-83282 hydraulic fluids and Mil-L-7808 lubricating oil, were tested in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) to define their Minimum Hot Surface Ignition Temperature (MHSIT's) when introduced as a spray or stream onto a hot engine bleed duct. The test employed a simple, uncluttered test section and a realistically simulated portion of the F-16 engine compartment. MHSIT's for all but Mil-H-83282 were consistently found to be higher than the fluids autoignition temperature.

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SUMMARY

Hot Surface Ignition Temperature (HSIT) testing was performed in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) located in building 71-B at Wright-Patterson Air Force Base. The objective of this test program was to measure Minimum Hot Surface Ignition Temperatures (MHSIT's) of five common aircraft fluids (Mil-H-5606 and Mil-H-83282 hydraulic fluids, JP-4 and JP-8 fuels and Mil-L-7808 lubricating oil) using an air-heated bleed-air duct in a high realism test article.

First, tests were conducted on a single piece of Inconel bleed duct in a bare engine compartment with sprays of JP-4 fuel and Mil-H-5606 hydraulic fluid. The purpose of these tests was to checkout systems and techniques and acquire data which could be directly compared with data from previous tests. (Results of these tests are presented in Table 4, page 59.)

Next, a simulation of a portion of the F-16 engine compartment was inserted into the AENFTS and the five aircraft fluids, JP-4 and JP-8 fuels, Mil-H-5606 and Mil-H-83282 hydraulic fluids and Mil-L-7808 lubricating oil were injected as spray or streams onto various locations on the hot bleed-air duct. Variables including ventilation air pressure, temperature, velocity and fluid flowrate were varied to study their effect on the MHSIT of these fluids. (Results of these tests are presented in Tables 7, 8 and 9, pages 73, 74 and 75.)

The lowest MHSIT's identified for each of the fluids at 14.4 psia and 120°F were:

- 5606's MHSIT was found to be 700°F when it was streamed onto the hot bleed duct at 2 ml/second with 1 ft/second ventilation airflow.

- 83282's MHSIT was found to be 750°F when it was sprayed on the hot bleed duct at 8 ml/second with both 0 and 4 ft/second ventilation airflow.

- 7808's MHSIT was found to be 990°F when it was streamed onto the hot bleed duct at 2 ml/second with 1 and 2 ft/second ventilation airflow.

- JP-4's MHSIT was found to be 1150°F when it was sprayed onto the hot bleed duct at 8 ml/second with 1 and 2 ft/second ventilation airflow.

- JP-8's MHSIT was found to be 1100°F when it was sprayed onto the hot bleed duct at 8 ml/second with 2 ft/second ventilation airflow.

Heating the ventilation airflow was found to reduce the MHSIT's for all five fluids. The effect of varying the ventilation airflow pressure on MHSIT's was complicated by the AENFTS's requirement for different airflows for altitude and ram simulation testing. In general, higher pressures produced lower MHSIT's, although none were identified at the highest pressure investigated (20 psia) which were lower than those noted above, probably because a higher airflow velocity was required to obtain this pressure.

Finally, the results were examined in light of simplified analyses of the key processes involved, such as chemical kinetics and droplet atomization, dynamics and heating/evaporation (for spray) and nucleate versus film boiling (for streams). Thus, the observed MHSIT differences and similarities between the various fluids and between sprays and streams were interpreted.

PREFACE

This is a final report of work conducted under F33615-84-C-2431 by the Boeing Military Airplane Company, Seattle, Washington, during the period May 1987 through August 1988. Program sponsorship and guidance are provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSF), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07 and Work Unit 94. Robert G. Clodfelter was the program manager.

The contents of this report cover a portion of the work defined under Task III of the contract, AEN (Aircraft Engine Nacelle) Test Requirements. In general, the task requires utilization of the AEN fire test simulator to establish the fire initiation, propagation, and damage effects exhibited by aircraft combustible fluids under representative dynamic operation environmental conditions, followed by the evaluation and development of protection measures.

Other documentation which has been submitted, as part of this contract, includes:

AFWAL-TR-87-2004 Effects of Aircraft Engine Bleed Air Duct Failures on Surrounding Aircraft Structure, April 1987.

AFWAL-TR-87-2060 Development and Evaluation of an Airplane Fuel Tank Ullage Composition Model:
- Volume I: Airplane Fuel Tank Ullage Computer Program, Oct. 1987.
- Volume II: Experimental Determination of Airplane Fuel Tank Ullage Composition, Oct. 1987.

AFWAL-TR-87-2089 Optical Fire Detector Testing in the Aircraft Engine Nacelle Fire Test Simulator, March 1988.

AFWAL-TR-88-2022 Fire Extinguishing Agent Evaluation in the Aircraft Engine Nacelle Fire Test Simulator, June 1988.

AFWAL-TR-88-2031 Advanced Air Separation Module Performance Evaluation, July 1988.

AFWAL-TR-88-2123 OBIGGS Preliminary Design Studies for A-6, P-3 and F-18 Aircraft (to be released about 28 Feb. 1989).

Boeing wishes to acknowledge with appreciation the contributions of N. Albert Moussa of BlazeTech Corporation, who joined this program in September of 1987 and helped with test planning, analysis and interpretation of data and documentation, and the technical personnel of SelectTech Services, Inc., in particular, A.J. Roth, who planned and performed the test and documented the test results.

A key Boeing contributor was C. L. Anderson, who provided technical guidance.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 INTRODUCTION

This report describes tests performed to define Hot Surface Ignition Temperature (HSIT's) for five fluids commonly found in an aircraft engine compartment, Mil-H-5606 and Mil-H-83282 hydraulic fluids, Mil-L-7808 lubricating oil and JP-4 and JP-8 fuels, when injected as sprays and steams onto a hot Inconel engine bleed duct. For simplicity, these fluids will henceforth be referred to as 5606, 83282, 7808, JP-4 and JP-8. These tests were performed to provide a better understanding of the mechanism and risk of hot surface ignition in an aircraft engine compartment and to improve the existing data base available to the aircraft designer.

The hot surface ignition tests were conducted with two test articles:

- a short section of bleed duct mounted in an uncluttered test section, heated alternately by electrical resistance heaters and by hot high-pressure air

- a F100-PW-200 engine right-side bleed duct mounted in a test section cluttered by actual engine components and simulated aircraft structure

The test facility employed, the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) is equipped so that the velocity, pressure and temperature of its airflow, simulating engine compartment ventilation air, could be varied to represent a variety of aircraft flight conditions.

1.1 Background

The Auto-Ignition Temperature (AIT) of the fluids present in an aircraft engine compartment is often used as a guideline when determining the maximum surface temperatures which should be allowed in the compartment. A fluid's AIT is that temperature at which its vapors will ignite in air at atmospheric pressure without an external source of ignition. Most published AIT data has been acquired in accordance with the method of ASTM

D 2155. ASTM D 2155 was recently replaced by ASTM E 659, which employs a larger flask and is considered to provide more reliable data.

AIT test conditions are much different than those in an aircraft engine compartment, so attempts have been made in the past to measure Minimum Hot Surface Ignition Temperatures (MHSIT's) that would more closely represent aircraft engine compartment component limit temperatures. MHSIT's above the AIT of the fluid, sometimes hundreds of degrees Fahrenheit higher, have been determined during past test programs.

A summary of the results of previous hot surface ignition studies (References 1 to 5) is given on Figure 1. The plotted temperatures should be reduced as noted for each study in order to estimate the temperature at which ignition would not occur. This is due to test methodology and measurement errors. A 5°F reduction in the ASTM D 2155 AIT value is acceptable due to the known precision of this test method.

Much of the past HSIT test work has been done with greatly simplified test articles which were intended to simulate hot surfaces, primarily bleed-air ducts, in aircraft engine compartments. The HSIT's determined in these tests varied considerably, probably because of differences in test methods and equipment. None of these tests employed a test article which closely simulated an actual aircraft engine compartment. Hence the aircraft engine compartment design information available from documentation of these programs has been difficult to use. A summary of prior test efforts follows:

<u>Rolls Royce</u>

In the mid-1960's, G. Beardsley of the Rolls-Royce Ltd. Aero Engine Division investigated the hot surface ignition of kerosene in a wind tunnel having an electrically heated floor (Ref. 1). The effect on hot surface ignition temperature of variation in the tunnel velocity and the presence of assorted turbulence causing obstructions on the tunnel floor was also investigated.

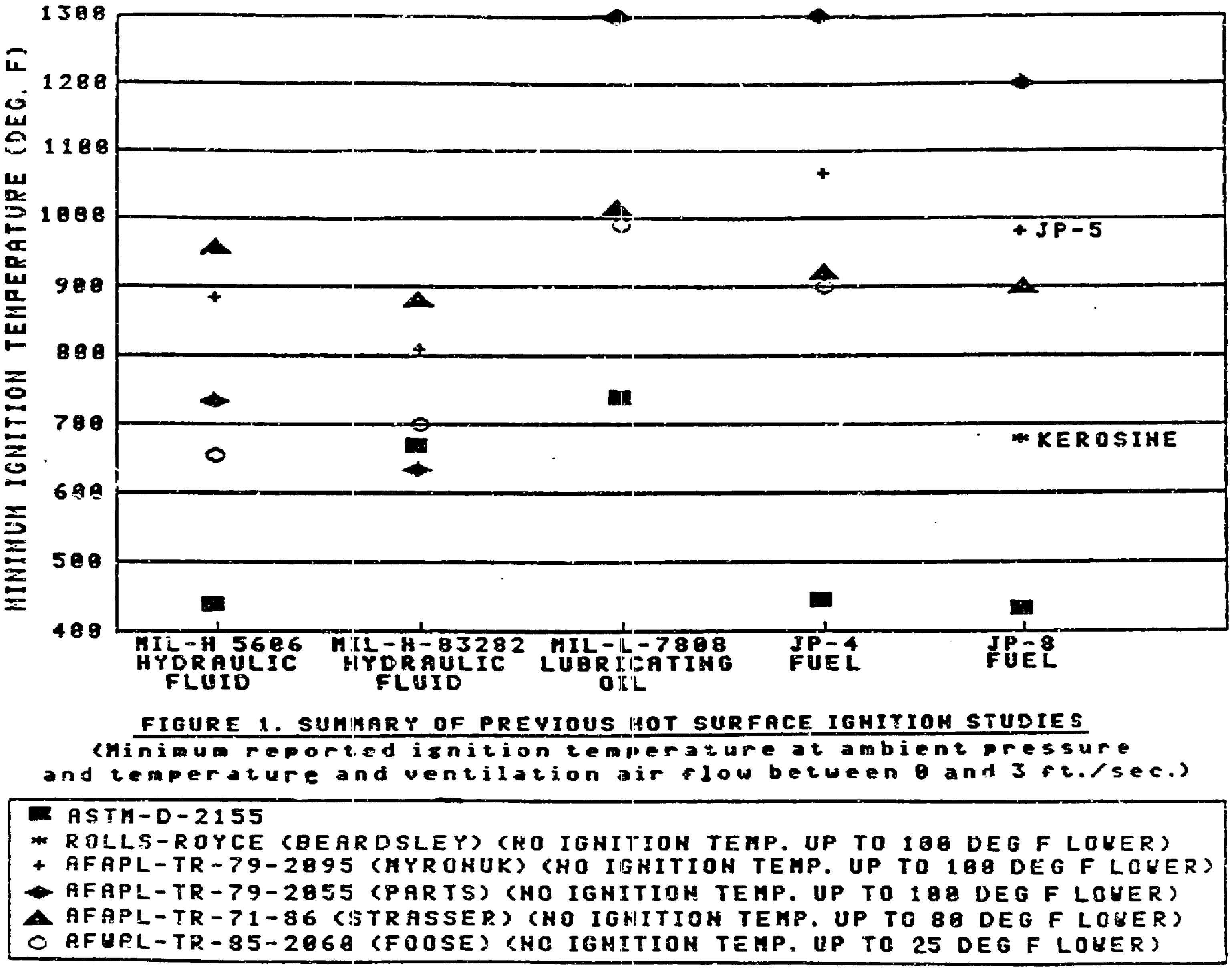


Figure 1. Summary of Results of Previous Hot Surface Ignition Studies

The tunnel employed in these tests was a rectangular low speed wind tunnel, about 3.9 inches high and 6.9 inches wide. The tunnel floor had an electrically heated working section 18 inches long. Ventilation air at room temperature and ambient pressure was supplied to the wind tunnel at velocities up to 10 ft/sec. Kerosene was sprayed onto the hot rectangular tunnel floor at 500 psig (3.6 - 3.8 ml total volume).

The test procedure that was followed was to select a tunnel floor temperature and a ventilation air velocity that would produce ignition and then increase the ventilation air velocity in increments of 0.1 ft/sec while the tunnel floor temperature was held constant until no ignition occurred. This was repeated and the lowest air velocity which did not produce ignition in 10 attempts was recorded. Air velocities sufficient to prevent ignition of the kerosene were determined for a range of tunnel floor temperatures from 700°F to 1472°F.

The effect on these hot surface ignition temperatures of the installation of a variety of obstructions on the tunnel floor was also investigated. These obstructions were made from steel, were 1 inch thick, varied in height (from 0.25 to 2.5 inches), width (from 1 inch to the full tunnel width) and distance from the tunnel exit (4, 7, 10 and 13 inches).

The effect of these obstructions on the hot surface ignition temperature varied with the size and location of the obstruction and with the tunnel floor temperature being tested. Installing the smaller obstructions generally resulted in higher airflow velocities being required to prevent ignition at a given tunnel floor temperature.

This study, while limited to kerosene, was one of earliest hot surface ignition test programs applicable to aircraft engine compartment design because, with its variety of flow obstructions, it did address the fact that engine compartments also have a variety of flow obstructions which create local velocity regions both above and below the average compartment velocity.

Myronuk

Myronuk (Ref. 2) studied the hot surface ignition of aircraft fluids in the late 1970's. A laboratory scale engine compartment fire simulation system at the Ames Research Center was used. The objective of this test program was to determine the MHSIT for a variety of fluids and to investigate the effect of the heated surface material, ventilation velocity, fluid flowrate, injection method and heated surface irregularities and obstructions on these MHSIT's. Aircraft fluids that were tested included JP-4, JP-5, 5606 and 83282. The test article used was a 30 $inch^2$ section of the outside surface of stainless steel or titanium alloy pipe, 3 inches in diameter and 39.4 inches long. The test article was heated by a premixed propane-air flame inside the test section.

Conclusions reached during this program included:

- o HSIT's increased for all fluids tested as ventilation velocity was increased

- o HSIT's were higher for more volatile fluids

- o HSIT's may not be inferred from the AIT's of the fluids

Measured MHSIT's for test fluids at 2.6 ft/sec velocity and 15 ml/sec fluid spray for 1 second (in 68^{o}F air at ambient pressure), 1058^{o}F for JP-4, 878^{o}F for 5606 and 797^{o}F for 8328, were all well above the AIT's for those fluids.

The nature of the test article and technique may have compromised the application of these results to aircraft engine compartment design: (1) The simulator used flame heated stainless steel or titanium pipe as its hot target. Since the surface material can affect the MHSIT, and inconel bleed ducts are frequently the hottest component in and aircraft engine compartment, this choice may introduced bias into the MHSIT data. (2) The test procedure called for increasing the surface temperature from one test to another until ignition was achieved. In the present program it was found that this technique led to falsely high MHSIT's. (3) The effects of air temperature and pressure on MHSIT's were not addressed.

Parts

Parts performed a series of aircraft fluid flammability tests in the late 1970's (Ref 3). Using equipment built at Monsanto for the test program, hydraulic fluid and lubricating oil AIT's, heats of combustion and MHSIT's were measured. A semi-automatic autoignition test apparatus comprised of a crucible furnace, a temperature controller and a Vycor flask was used to measure fluid AIT's and a oxygen bomb calorimeter was used to determine the heats of combustion of the test fluids.

The determination of hot surface ignition temperatures was performed on a hot manifold ignition test apparatus (Federal Test Method Standard No. 791B, Method 6053, 15 January, 1969). The test apparatus consisted of a stainless steel box with the hot target, a resistance heated 24 inch long, 3 inch diameter stainless steel pipe, suspended inside the box. Fluid was sprayed through an oil burner nozzle (hollow cone, 80 degree spray-angle, rated at 1.5 gph for oil at 100 psig). All test injections were made at a pressure of 1000 psi for 1 second. Fluid streams were supplied by burettes of three different sizes (flowrate = 0.35 ml/sec, 1.0 ml/sec, 1.7 ml/sec) and up to 25 ml were injected during each test.

The lowest minimum hot surface ignition temperatures recorded were 730°F for 5606, 630°F for 83292 (below the fluid's AIT) and 1300°F for 7808 and JP-4 and 1200°F for JP-8. Streams of fluid appeared to ignite at lower surface temperatures than sprays.

As there were no provisions for ventilating the test article in a controlled manner, the Parts test program did not address the effect of ventilation air velocity, temperature or pressure on MHSIT. Because ventilation airflow velocity has been found to have a major effect on MHSIT's, these data cannot be directly applied to ventilated aircraft engine compartment design. Because the test article was fabricated of stainless steel and heated electrically, some additional deviation from the actual hot surface ignition situation found in a normal aircraft engine compartment could be expected.

Strasser

Strasser performed hot surface ignition tests using JP-4, JP-8, 5606, 83282 and 7808 (Ref. 4). The fluids were injected (in a stream at various flowrates) onto the hot surface, a cylindrical target 1, 2 or 4 inches in diameter or a flat rectangular target. The target was electrically heated and was suspended in an 8 inch diameter tube which could be ventilated with air from a compressor. The ventilation air could be heated to 350°F at 200 scfm.

It was found that the MHSIT's of the test fluids increased with increasing ventilation velocity. Increasing the ventilation air temperature, however, produced lower MHSIT's. The lowest MHSIT's in 80°F air were 920°F for JP-4, 900°F for JP-8, 930°F for 5606, 880°F for 83282 and 1010°F for 7808 for ventilation airflow up to 2 ft/second.

Application of these results to engine compartment design is complicated by the use of an unobstructed 8 inch diameter tube for ventilation, the airflow within an aircraft engine compartment normally being complicated by the presence of a jumble of engine components and aircraft structure. In addition, the use of electrical resistance heating and stainless steel targets provides further complication.

Foose

In 1982, J. G. Foose of General Dynamics performed hot surface ignition temperature tests in the same test facility employed for the current program. This work is documented in Appendix A of Reference 5. The objective of this test program was to examine the feasibility of removing insulation from F100-PW-200 engine bleed-air ducts in the F-16 engine compartment.

An electrically heated test article composed of two six inch segments of the 13th stage bleed-air duct from an F-16 engine was used to determine the MHSIT's for sprays and streams of 5606, 83282, JP-4 and 7808, directed onto the hot bleed-air duct. To enhance ventilation airflow simulation, a cushion loop clamp for the bleed-air duct and engine compartment obstructions, including the augmentor fuel pump controller and a portion of the oil-air heat exchanger tank, were added to the test article for some test conditions. This test article was mounted in the AENFTS allowing simulation of ventilation airflow velocities from 0 to 10 ft/sec.

The minimum MHSITs measured during this program at a ventilation velocity of 6 ft/sec in air, at ambient pressure and temperature, were:

- $1100^{o}F$ for JP-4 (streamed onto duct with cushion clamp and onto duct with flow obstructions)
- $1025^{o}F$ for 5606 (streamed onto duct with clamp)
- $950^{o}F$ for 83282 (streamed onto duct with obstructions)
- $1325^{o}F$ for 7808 (spray onto bare duct).

After analysis of the data acquired in these tests, it was concluded that the risk associated with the omission of the bleed duct insulation was acceptable because of the infrequent occurrence of the maximum bleed duct temperatures during flight, even though estimated bleed duct operating temperatures could occasionally exceed the measured ignition temperatures of the test fluids.

The General Dynamics program addressed a number of important aircraft engine compartment hot surface ignition variables. These included fluid injection method, the effect of engine compartment clutter (such as the cushion clamp and heat exchanger oil tank) and the effect of ventilation velocity

While the engine compartment simulation employed in these tests was much more realistic than in earlier programs, there were some compromises:

- Two short lengths of electrically heated inconel tubing were used to simulate the F-16's bleed duct. Fluids impinging on the surface may have behaved differently if the duct had been air heated

- Only two airflow obstructions were used while the F-16 engine compartment is crowded with obstructions

- Variation in ventilation air pressure and temperature representing complete F-16 flight conditions was not included

The current program was planned to enhance the data base developed in these tests.

1.2 Objective

The objective of the first part of the program, the simple duct tests, was to investigate the phenomenon of hot surface ignition of flammable fluids within an aircraft engine compartment with a test article that was simple enough to allow control of most of the test variables. This part of the program was planned to allow:

- comparison to past data, especially the General Dynamics data (Appendix A of Reference 5)

- determining the differences between an electrically heated duct and an air heated duct

- determining the differences between selected aircraft fluids

- investigating the effect of a cushion clamp

- investigating the effect of duct orientation (horizontal or vertical)

The objective of the second part of the program, the high realism tests, was to determine the minimum hot surface ignition temperatures for each aircraft fluid of interest over a range of severe but realistic aircraft operating conditions. These tests were intended to provide design information that had previously been unavailable concerning safe surface temperature limits within aircraft engine compartments based on the actual flammable fluids present and the temperature, pressure and velocity of the compartment ventilation airflow.

1.3 Approach

For the first part, a seven inch long section of 1.5 inch OD inconel tubing, 0.036 inch thick, was employed as a hot target. It could be heated, either electrically or, with hot air (Fig. 2). This duct and a spray nozzle were placed in the otherwise empty test section of the AENFTS. MHSIT tests were run with JP-4 and 5606. The same cushion clamp as used in the earlier General Dynamics tests was added to the duct for some of these tests. These tests were run to:

- o checkout the facility and test article and provide a data baseline
- o compare MHSIT data acquired with this simple test article with the data acquired in the Reference 5 (General Dynamics) tests.
- o compare data acquired with electrical and hot-air heating

For the second part of the program, a more complex test article was installed in the AENFTS test section. A simulation of the right side of the F-16 engine compartment, which had been built for earlier AENFTS testing (Refs. 5, 6 and 7), was reworked so that hot-air from the AENFTS bleed-air heating system was routed through an actual F-16 engine bleed-air duct installed in a representative jumble of plumbing, pumps, tanks and clamps (Fig. 3). A spray nozzle and drip lines were added so that the flammable fluids of interest could be sprayed or introduced as a stream to various locations on the heated bleed duct.

Experiments were conducted with 5606, 83282, 7808, JP-4 and JP-8 entrained onto the hot bleed duct to define realistic MHSIT values for the fluids. Initially tests were conducted to establish the method of flammable fluid delivery (spray or drip, fluid flowrate and duration) and delivery location which produced the lowest MHSIT's for each fluid. The ventilation airflow velocity, pressure and temperature were varied to define MHSIT sensitivity to these parameters.

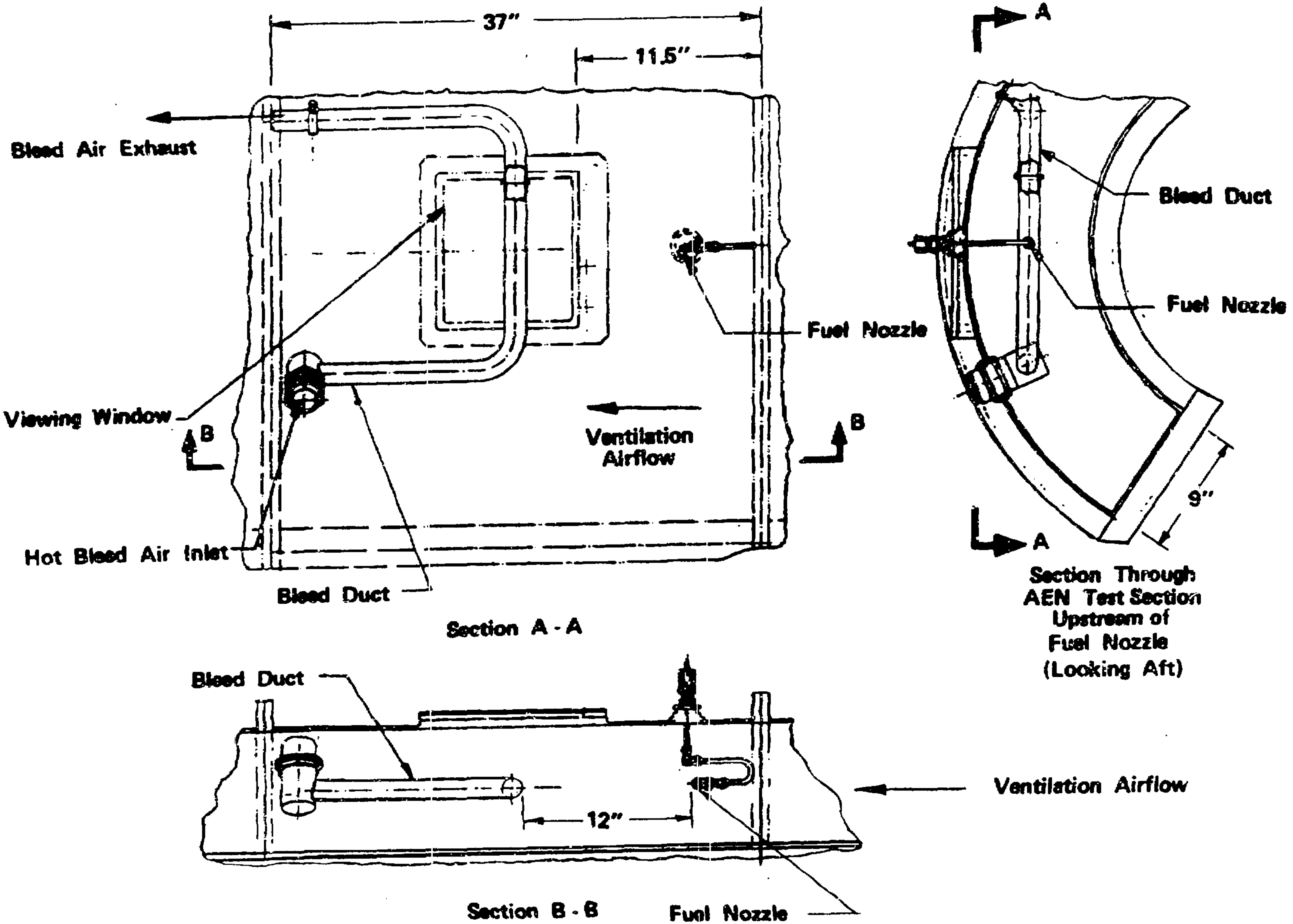


Figure 2. Simple Duct Test Article

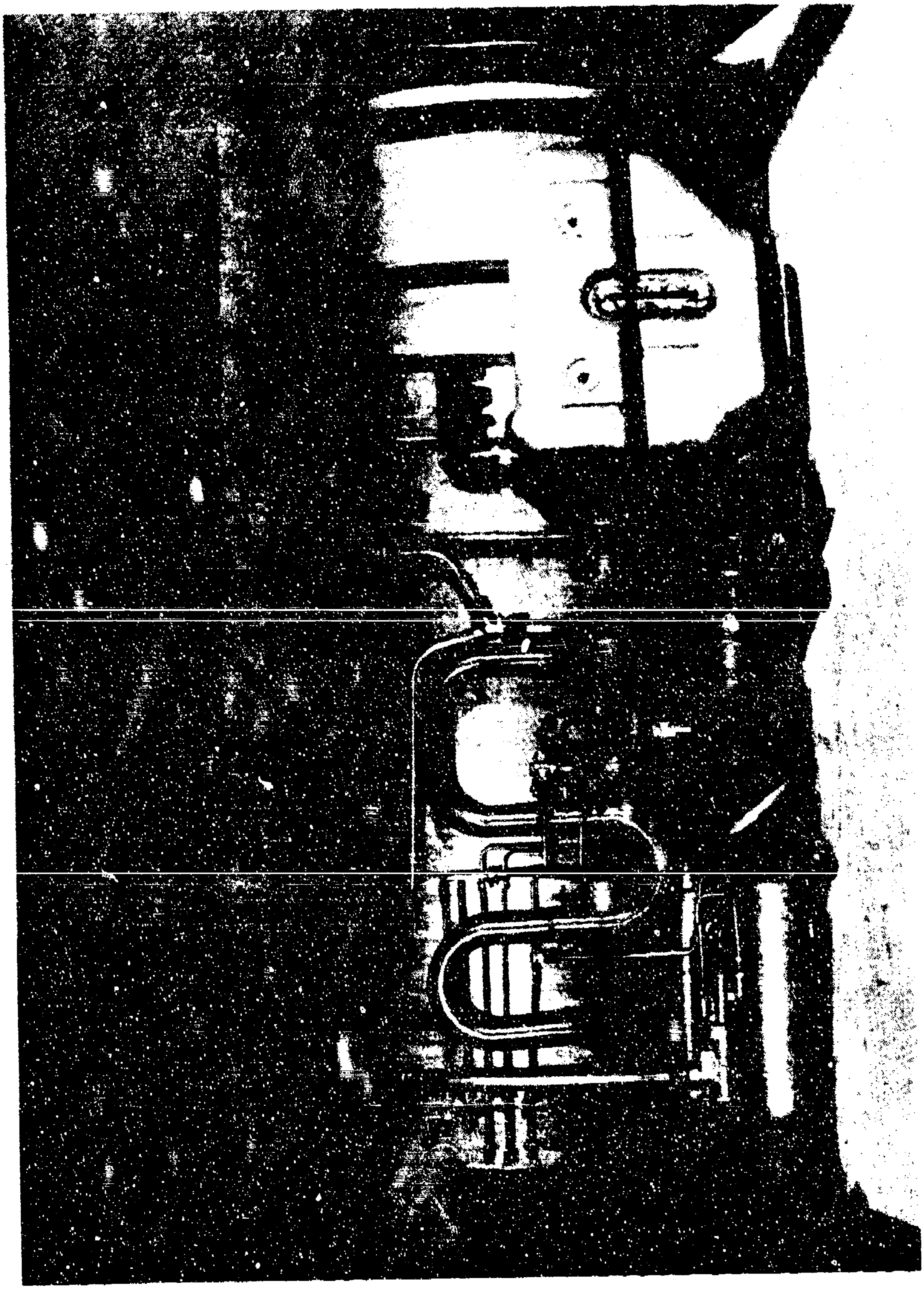


Figure 3. High Realism Test Article

2.0 TEST FACILITIES

2.1 AENFTS Facility

The AENFTS is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine. The AENFTS is installed in I-Bay of Building 71-B, Area B, Wright-Patterson Air Force Base, Ohio. This facility (Fig. 4) includes air delivery and conditioning equipment designed to simulate engine compartment ventilation airflow, a test section within which fire testing can safely be conducted, and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere. In addition, it includes a gas fired heating system to provide simulated engine bleed-air to the test section.

The test section of the AENFTS (Fig. 5) is a two radian (114 degree) segment of the annulus between a 15 inch-radius duct, which simulates an engine case, and a 24 inch radius duct, which simulates the engine compartment outer wall. The test section is approximately 14 feet long and is equipped with access ports and viewing windows that are provided for access to test equipment and instrumentation and for observation of the test activities taking place within.

As shown in Figure 4, the AENFTS ventilation airflow conditioning systems include a blower that provides air at atmospheric pressure (to simulate low speed sea level flight conditions), a high pressure compressor and air storage bottle farm to provide ventilation airflow simulating ram pressure in low altitude supersonic flight conditions and an air driven ejector (to evacuate the test section to simulate high altitude flight conditions). The airflow from the atmospheric blower or from the air storage bottle farm can be heated (without vitiation of the ventilation airflow) using 5 100 KW immersion heaters. The shorter curved test section wall, which simulates the case of a turbojet or turbofan engine, can be heated with radiant heaters. These heaters were not used in the current program, however.

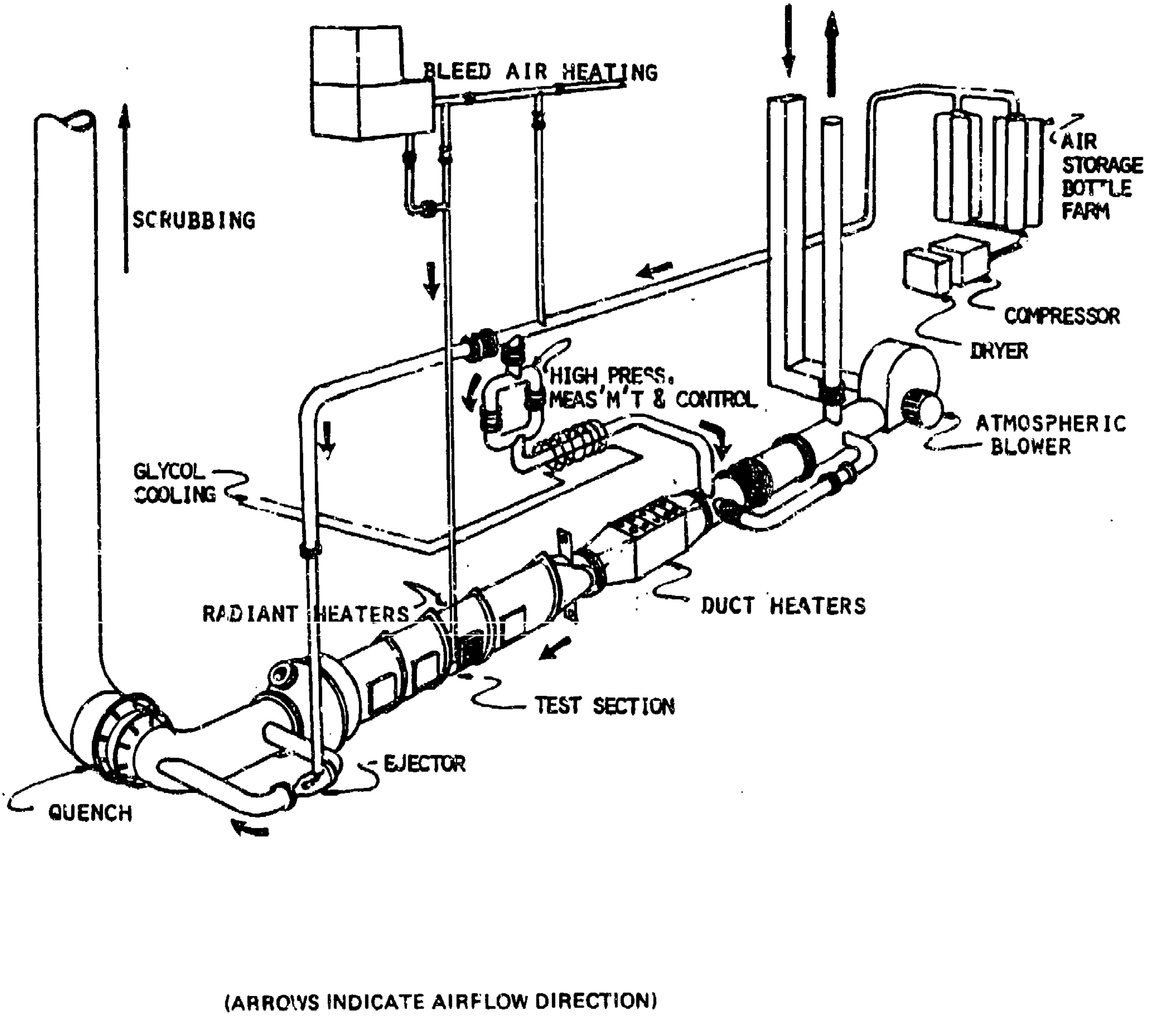


Figure 4. AENFTS Facility

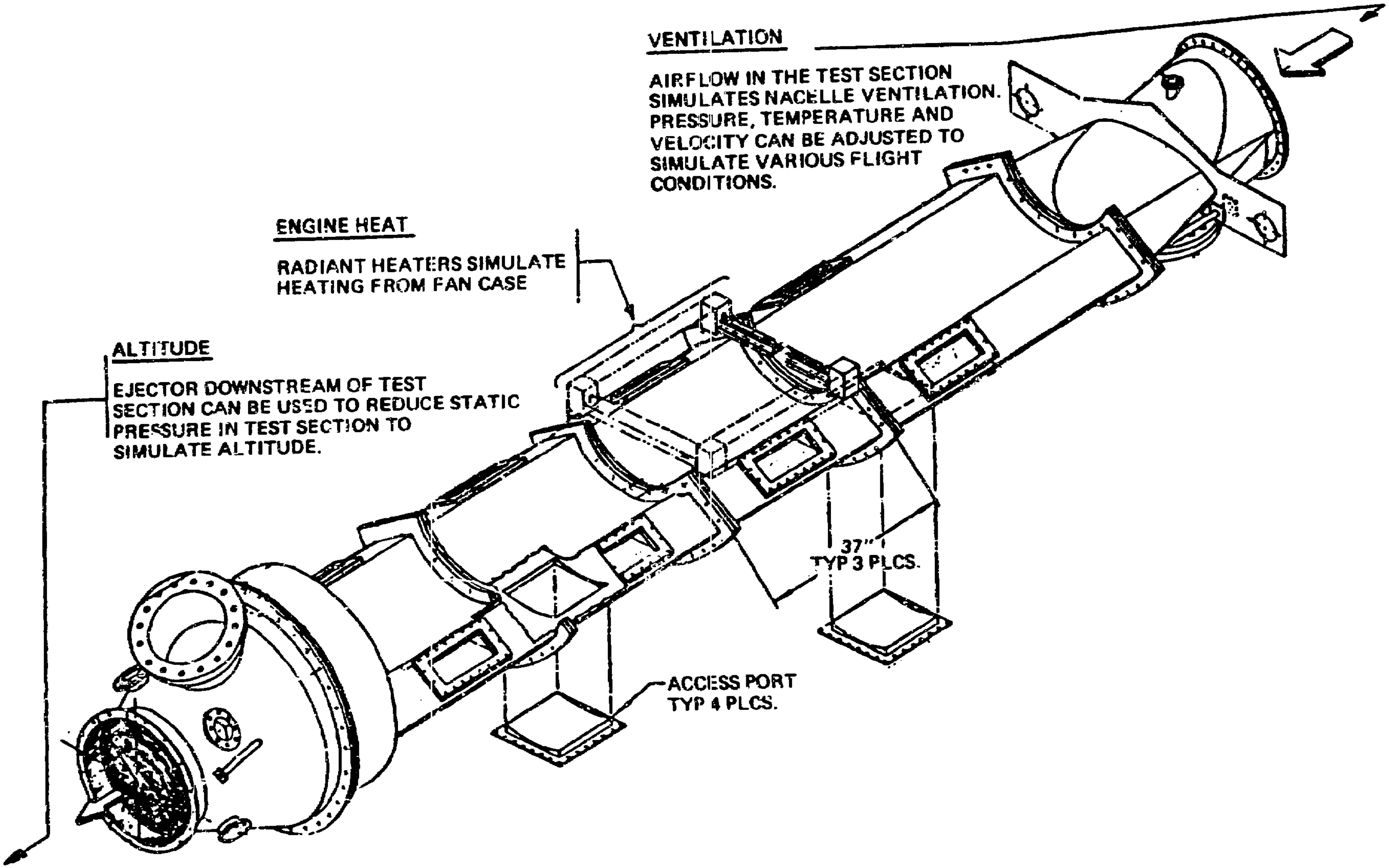


Figure 5. AENFTS Test Section

Simulation of the hazards associated with hot engine bleed ducts and the leakage that might result from damage to bleed ducts or the engine case is provided by the AENFTS bleed-air heating system. (See Reference 8 for experimental determination of damage results from bleed air leakage.)

This system consists of a natural gas fired heater with automated flowrate, pressure and temperature control systems which heated incoming high-pressure air from the air-storage bottle farm. Up to 1500°F and 220 psia could be provided at flowrates up to 1 pound per second. An insulated flex duct delivers this heated simulated engine bleed to the AENFTS test section

2.1.1 F-16 Nacelle Simulator

In an actual aircraft engine compartment, the ventilation airflow does not flow uniformly as in the clean AENFTS test section. Regions of reverse flow and flow stagnation have been seen in the F-111 being tested by the Federal Aviation Administration's Technical Center (Ref. 6) and the F-111 engine compartment is cleaner and designed for higher ventilation airflow rates than the F-16 engine compartment. To simulate a more realistic environment, having the complex of tubes, ribs, clamps, wires, and other flow disturbances of a real aircraft engine compartment, a portion of the F-16 nacelle was simulated for earlier testing in the AENFTS (Refs. 5, 6 and 7). This test article was found to be suitable for the present program.

The forward right side of the F-100 engine, as it exists in the portion of the F-16 engine compartment selected for simulation, is shown in Figure 6. A scrap early prototype F-100 engine was obtained and the components in this region were removed and installed on a 5 foot-long simulated engine side stainless steel base plate constructed to fit the engine side of the AENFTS test section (Fig. 7). Intrusion into this region of the F-16's glove tank and structural ribs was simulated in sheet metal (Figs. 8, 9 and 10) and fitted into the AENFTS test section over the engine side base plate (Fig. 11). The final assembly represented one-third of the engine compartment annulus. The remaining AENFTS test section length,

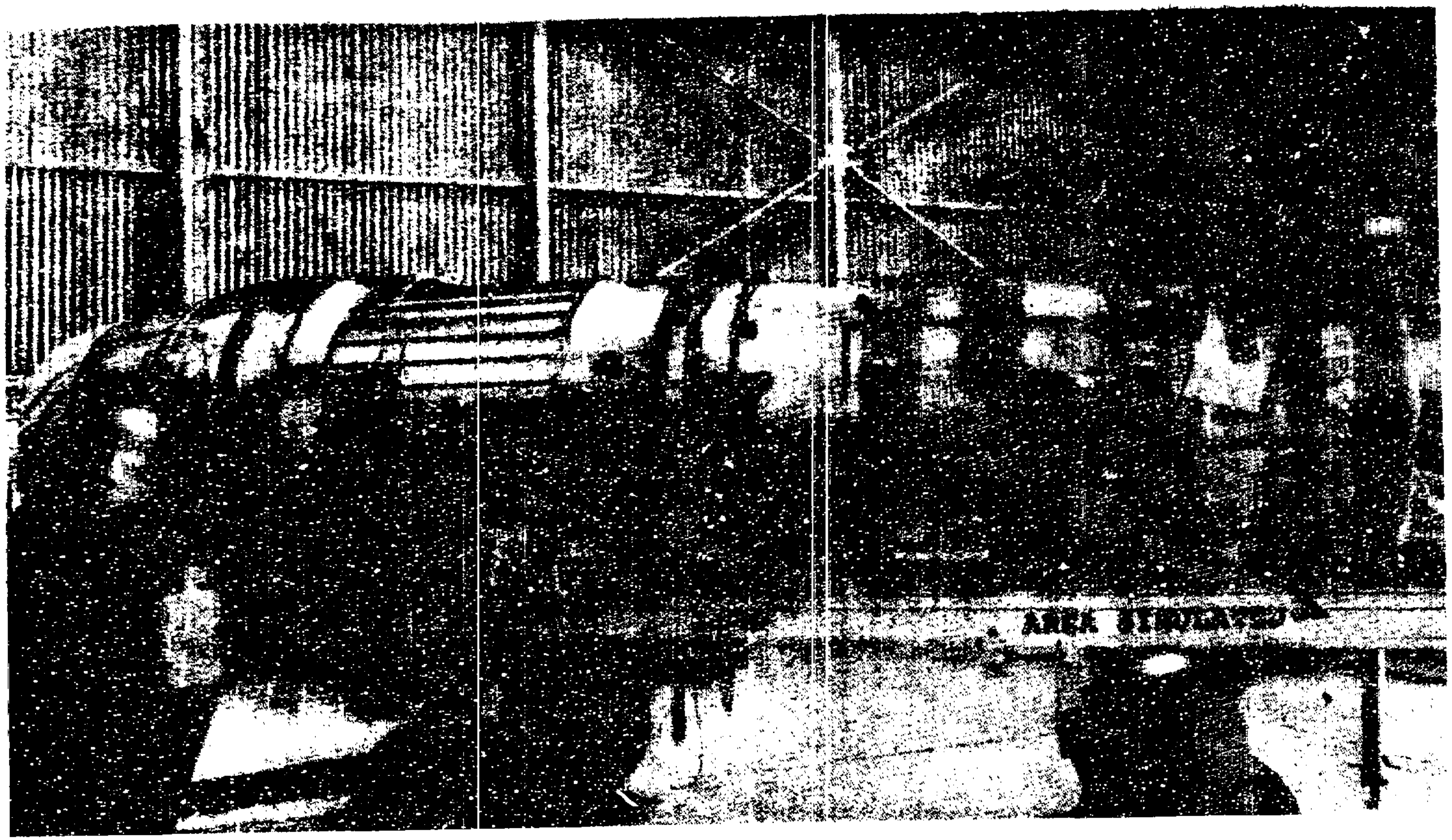


Figure 6. F-100 Engine Showing Accessories for F-16 Simulator

Figure 7. F-16 Simulator Engine Side

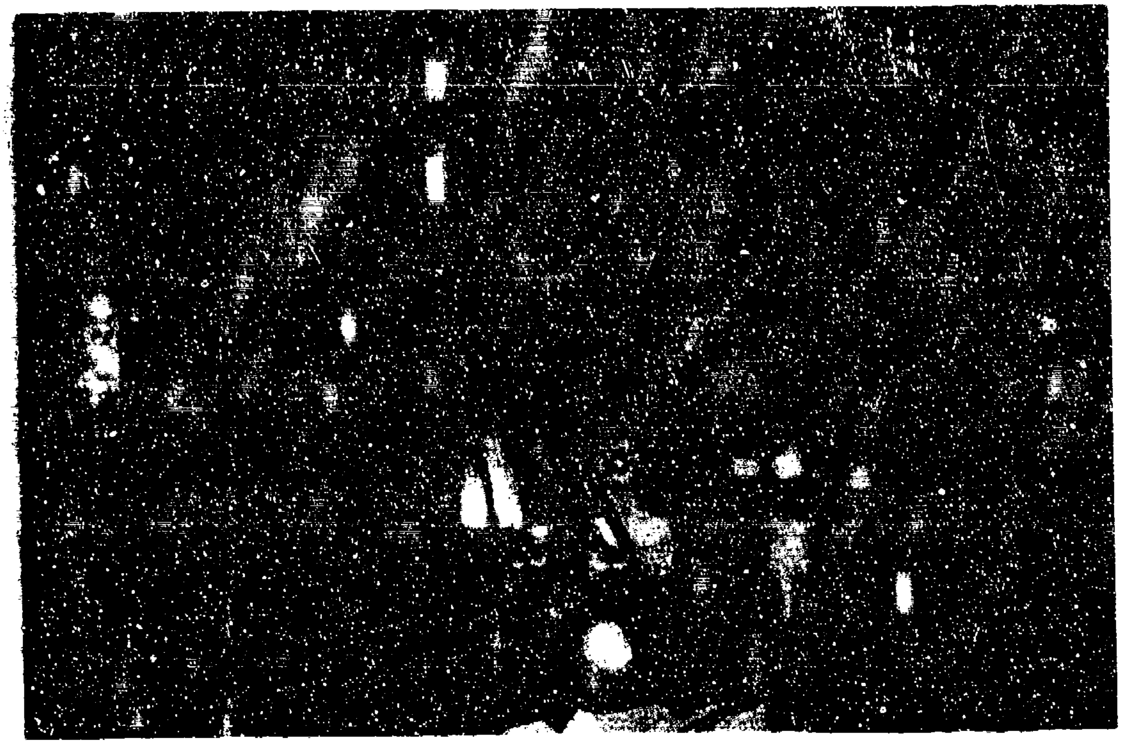


Figure 8. Rear View of F-16 Simulator Prior to Installation

Figure 9 Front View of F-16 Simulator Prior to Installation

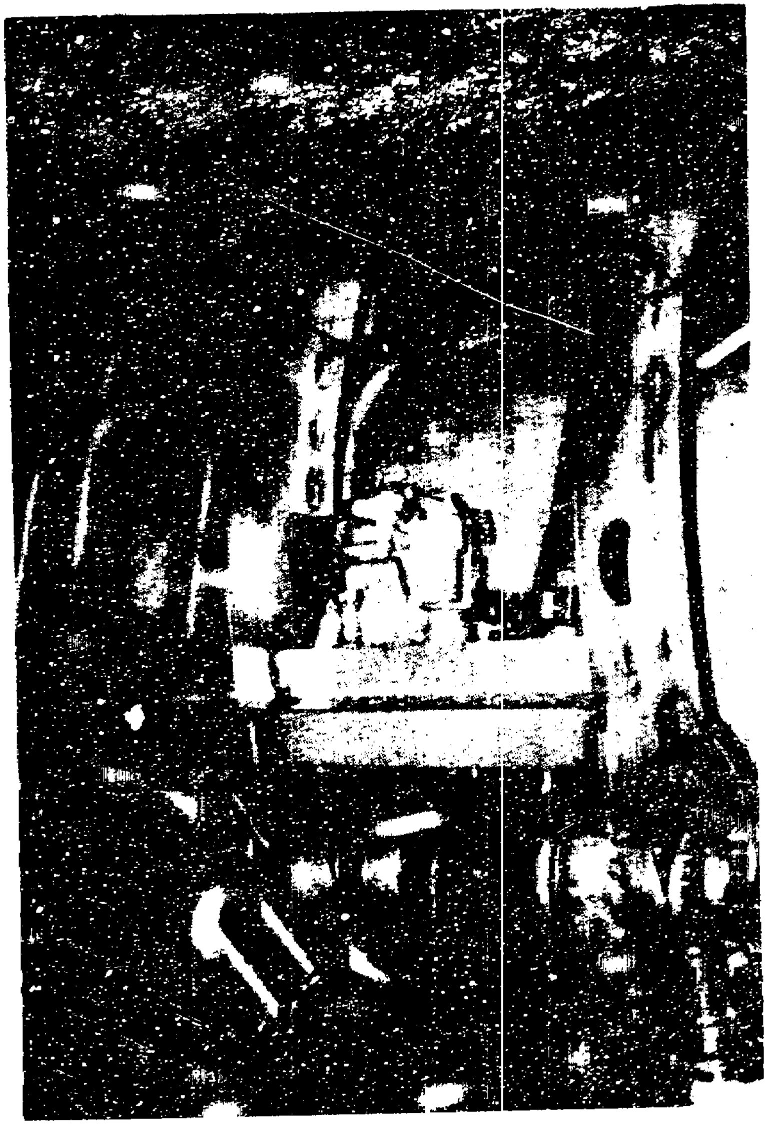


Figure 10. Closeup of Fire Zone of F-16 Nacelle Simulator

Figure 11. F-16 Nacelle Simulator Installed in AEN Test Section

approximately 60 inches, simulated the less cluttered annulus around the afterburner.

Fused quartz viewing windows were provided in the 15 inch square access ports on the nacelle side of the AENFTS. One of these opened onto the forward "arch" of the F-16 bleed duct.

The distribution of the ventilation airflow through the F-16 nacelle simulator was modified, for one series of tests, by the installation of a baffle plate at its upstream end. As shown in Figure 12, the baffle redirected the airflow upward so that local velocities around the hot bleed duct would be lower.

2.1.2 Fluid Delivery System.

Two fluid injection methods were used in the hot surface ignition test program. Spray was used in both the simple duct and high realism tests and additionally stream injection was used in the high realism tests. Both spray and stream were part of a fluid delivery system shown in Figure 13.

Nitrogen gas was used to pressurize the stainless steel 2 and 3 liter Hoke cylinders that were used as fluid reservoirs. The pressure of the fluid reservoirs was monitored with a pressure transducer and the pressure was displayed on the AENFTS console in the control room. The pressure was controlled by operating a three position switch on the AENFTS console. The fluid reservoirs were pressurized to 100 psig for stream injection, and from 105 to 135 psig for 8 ml/sec spray, depending on the fluid being sprayed. Lower reservoir pressures were required for fluids such as JP-4 and JP-8 while higher pressures were needed to achieve the proper spray flowrate for 5606 and 83282 and 7808, fluids with higher specific gravities and viscosities.

From the fluid reservoirs the fluid moved through 0.25 inch diameter stainless tubing to a filter and then to an air actuated ball valve that was connected to a switch and a timer located on the AENFTS console in the

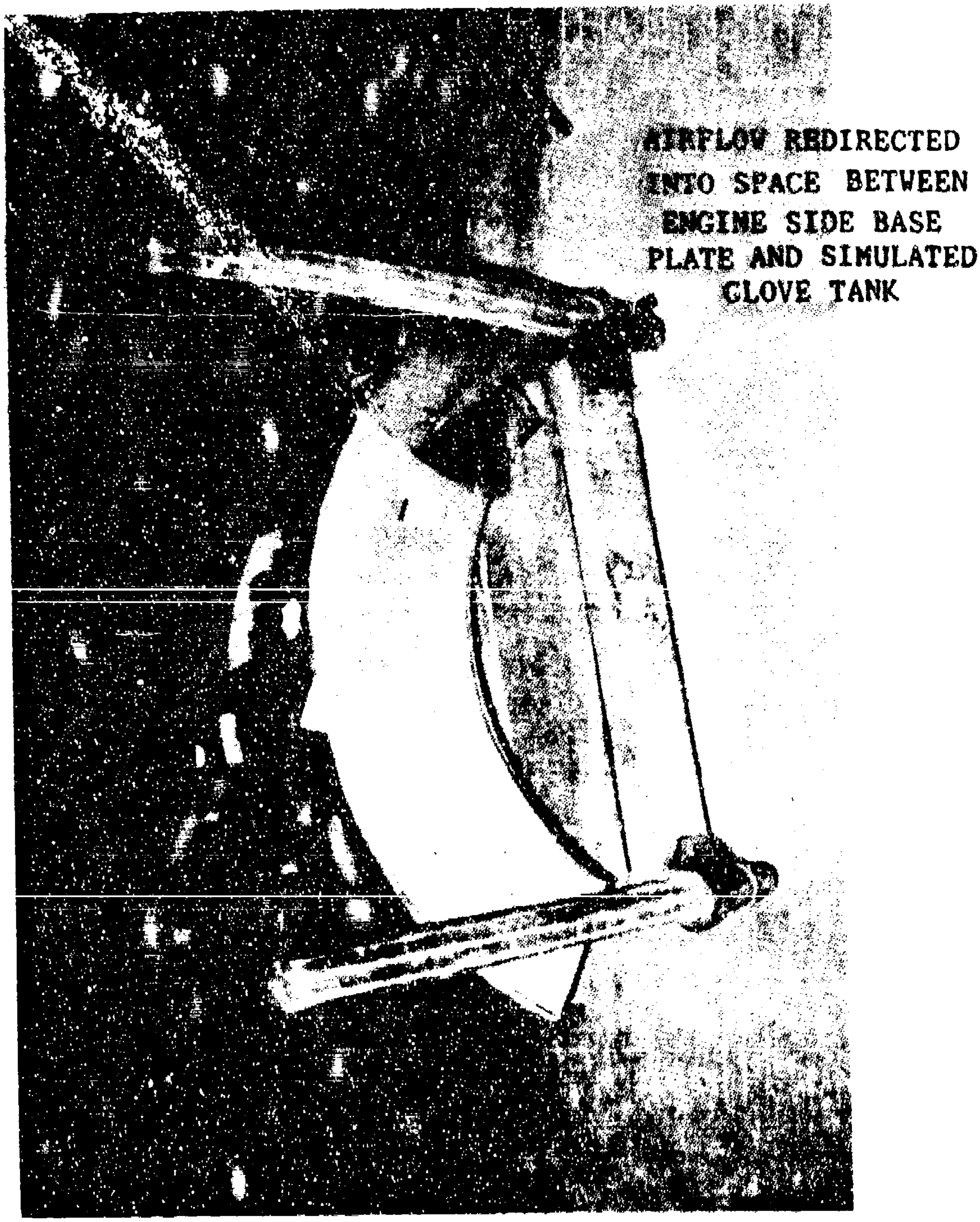


Figure 12. Installation of Baffle to Redirect Airflow in F-16 Simulator

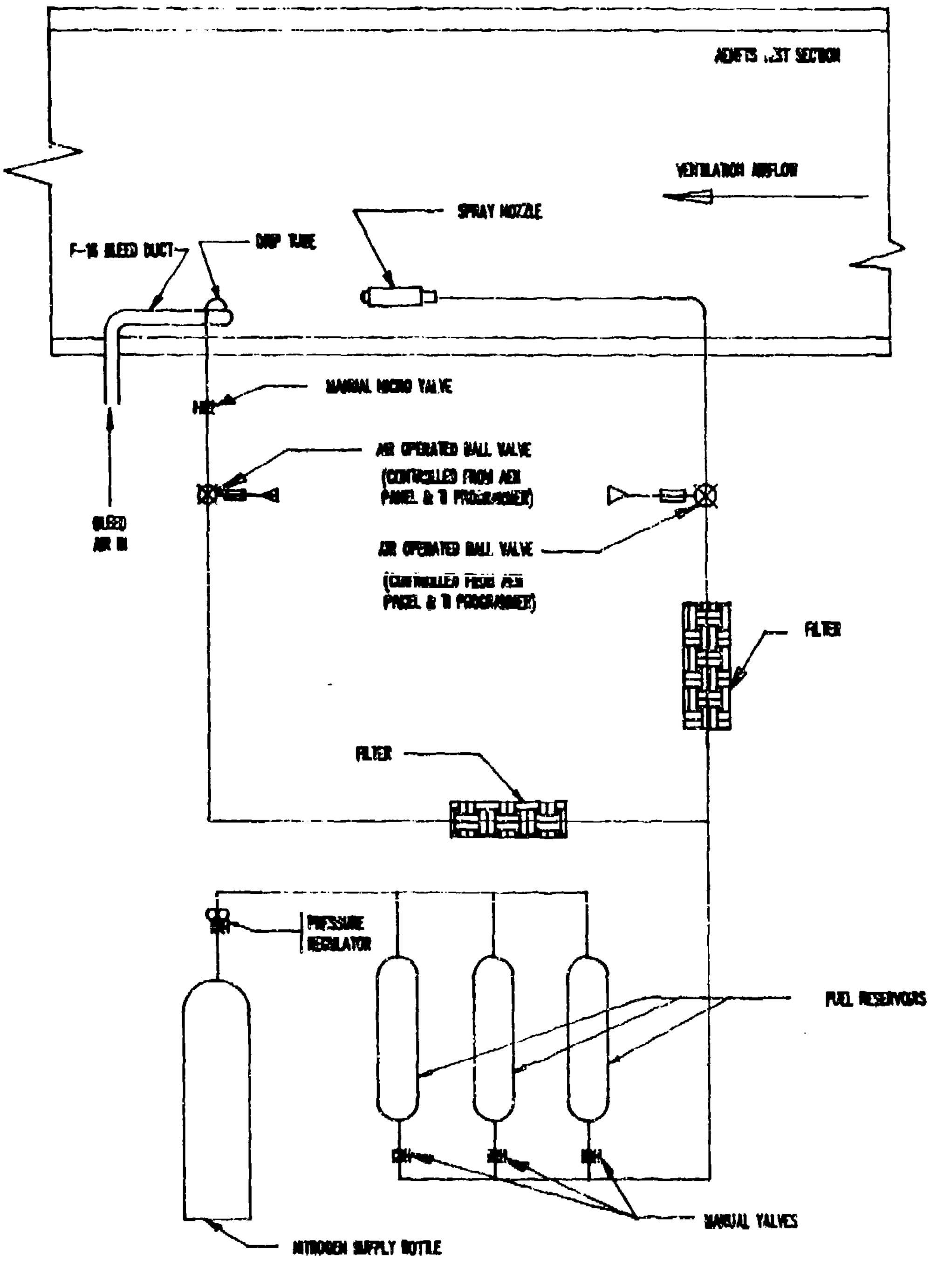


Figure 13. Schematic Diagram of Fuel Injection System

control room. Spray was normally injected at 8 ml/sec for 5 seconds and stream was normally injected at 2 ml/sec for 10 seconds. These values were chosen because they were in the middle of the range used for the General Dynamics tests (Appendix A of Ref. 5) but variation in their magnitude was subsequently found to have little effect on the MHSIT's.

The two fluid introduction methods utilized slightly different hardware. During the simple duct testing, the spray nozzle was always located 12 inches upstream of the leading edge of the simple duct. For the high realism tests, two nozzle positions were used, one upstream, about 12 inches ahead of the F-16 bleed duct (the spray being directed in the same direction as the ventilation airflow), and the other downstream, about 12 inches aft of the aft end of the F-16 bleed duct (the spray being directed against the ventilation airflow). In both cases the fluid line passed directly from the ball valve to the spray nozzle, a Wagner 621 nozzle with a 0.021 inch equivalent diameter orifice and a 6 inch flat spray halfwidth at 12 inches from the nozzle.

When a stream of fluid was employed, the fluid passed through a micrometering valve after leaving the ball valve. This valve controlled fluid flowrate from 1 to 3 ml/sec and the normal setting was 2 ml/sec. One of six fluid stream injection lines (0.070 inch I.D.) was connected to the output of the micrometering valve to select the injection location desired. The fluid stream tube exit was normal to the bleed duct surface and about 1/2 inch from the duct surface. A "T" was installed in each stream injection line outside the AENFTS so that compressed air could be used to clear the line of fluid after the completion of a test. Hence the next injection used room temperature fluid from outside the AENFTS, rather than preheated fluid that had been sitting in the stream injection line in the hot nacelle. The ball valve timer then was adjusted to allow for the filling of the empty stream injection line so that the net stream injection time for each stream location was 10 seconds.

2.2 Test Article

2.2.1 Simple Duct Test Apparatus

The simple duct was a seven inch long straight piece of uninsulated Inconel tubing (Fig. 14, 15 and 16). It had an outside diameter of 1.5 inches and a wall thickness of 0.036 inch. On either side of the seven inch bare surface of Inconel, the duct was insulated with Fiberfax ceramic putty and ceramic cloth and covered with fiberglass tape in order to restrict ignitions to occurring on the portion of the Inconel duct that was instrumented with thermocouples. During testing it was observed that fires were ignited only on the bare metal portion of the duct.

Figure 17 shows the placement and numbering of the thermocouples. Thermocouples 1 through 4 were placed radially around the duct 3.5 inches from the insulated edge, starting with thermocouple 4 on the leading edge of the duct. Thermocouple 1 was tack-welded on the top, 2 on the rear edge of the duct and thermocouple 3 on the bottom of the duct. The remainder of the thermocouples, number 5 through 8, were placed on the leading edge of the duct spaced one inch apart. All thermocouples were Type K Chromel-Alumel.

Two methods of heating the duct were available (Fig. 14). The electrical resistance heating method used three 1 KW Watlow Firerod resistance heaters mounted every 120^{o} in a 6.5 inch steel cylinder that slid snugly into the Inconel duct. These were the same heaters and steel cylinder as had been used in the General Dynamics (Ref. 5) tests. Voltage to the resistance heaters was manually controlled from the control room using a simple 3-position switch and the duct temperature was observed on console monitor. The duct could also be heated by air from the AENFTS bleed-air heating system. The hot air was then mixed with cold high-pressure air to control its temperature and then piped to the test article. The mixing valve was also controlled manually while observing the duct temperature indicated for location 3 (Fig. 17) on the the console monitor. Duct temperature for both the simple duct and high realism tests was controlled prior to injection but not during injection. After flowing through the

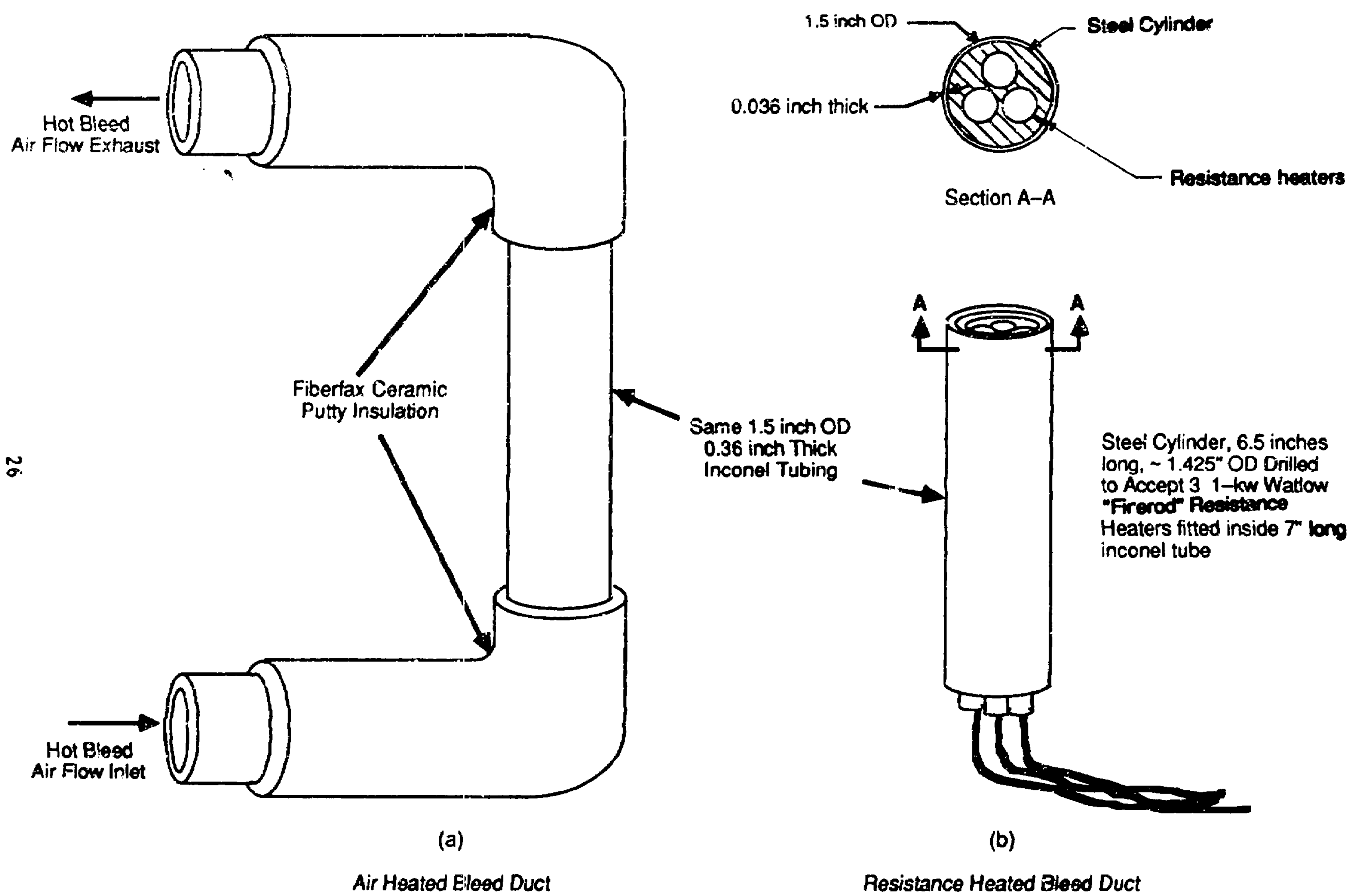
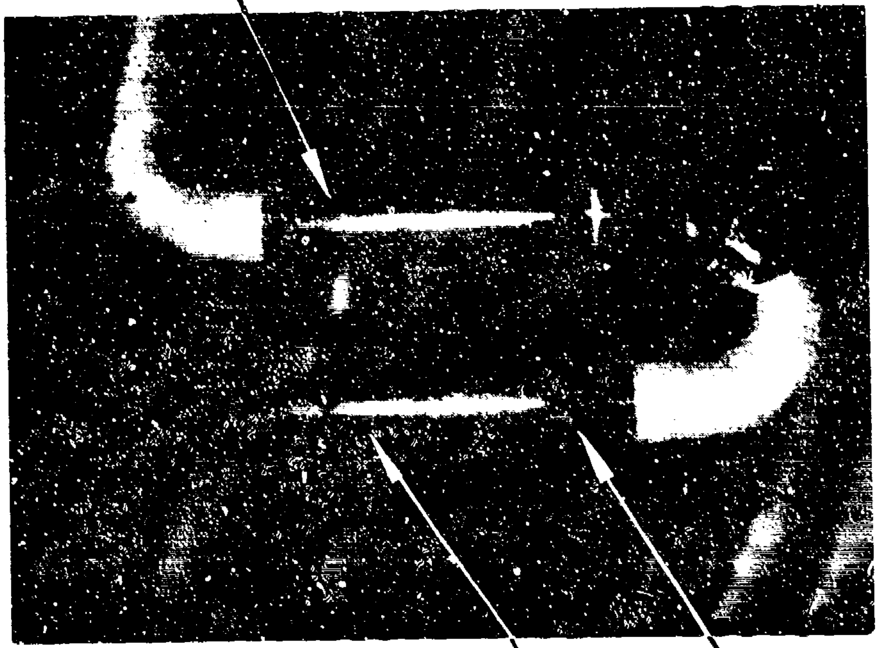


Figure 14. Details of Hot Air and Electrically Heated Simple Duct Test Articles

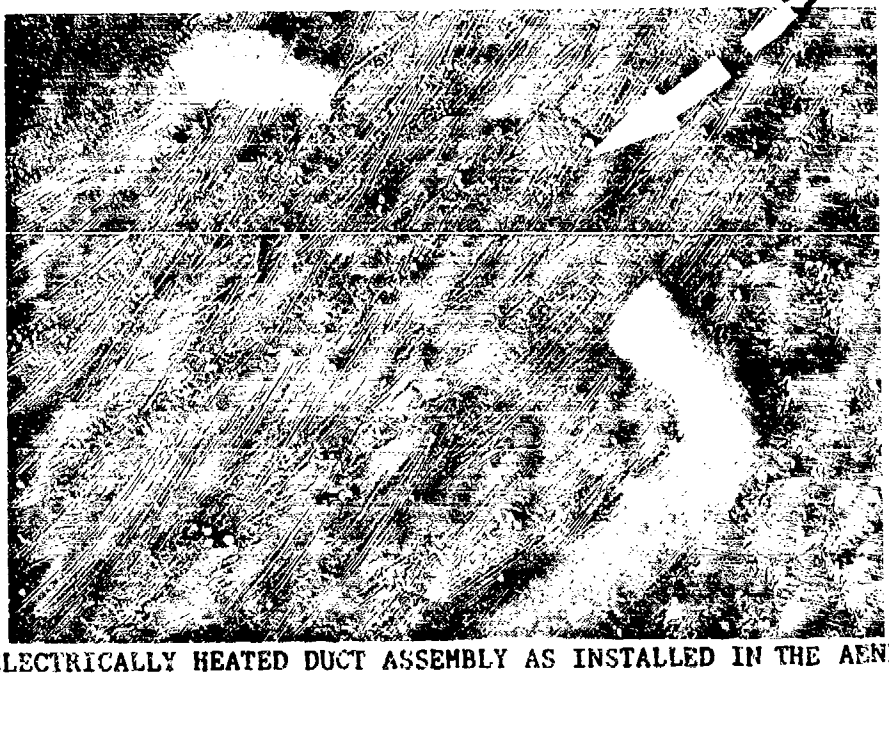
7 INCH LONG, 1.5 INCH OD, 0.36 INCH THICK INCONEL TUBING



STEEL CORE DRILLED TO ACCEPT "FIREROD" UNITS

THREE "FIREROD" 1-KW RESISTANCE HEATERS

VENTILATION AIRFLOW



ELECTRICALLY HEATED DUCT ASSEMBLY AS INSTALLED IN THE AENFTS

Figure 15. Electrically Heated Simple Duct Test Article

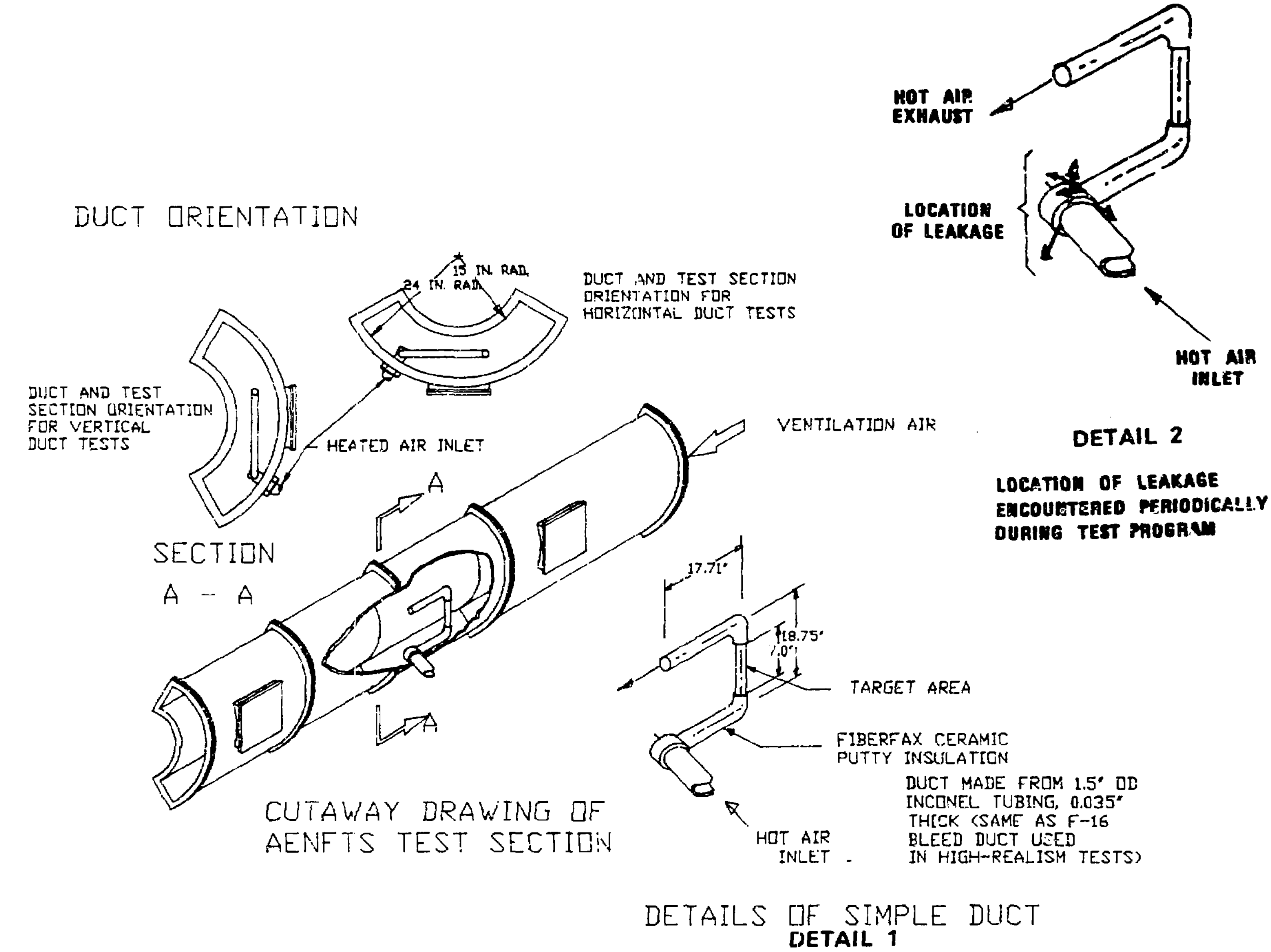
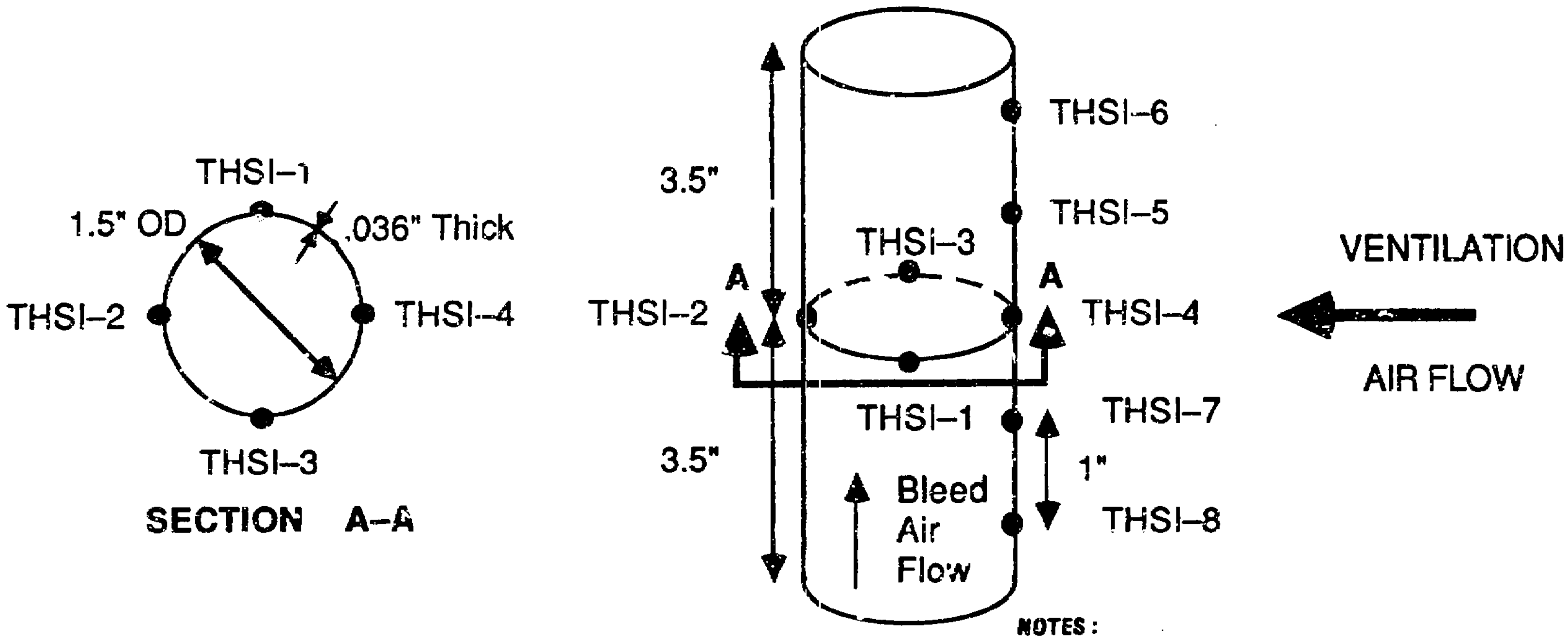


Figure 16. Cutaway Drawing of Simple Duct Test Article



NOTES:

1. THERMOCOUPLE LOCATIONS FOR HIGH REALISM TEST ARTICLE SHOWN ON FIGURE 21.

2. THE REFERENCE 5 TEST PROGRAM (FOOSE OF GENERAL DYNAMICS) DISTRIBUTED THERMOCOUPLES OVER TWO HEATED SECTIONS OF SIMULATED BLEED DUCT (PAGES A-25 AND A-26) OF REF. 5

Figure 17. Simple Duct Thermocouple Locations

simulated bleed air duct, the heated air was piped outside the AENFTS test section and exhausted near the ceiling of the room.

The thermocouples read uniformly (within $\pm$ 20°F) when the test section was air heated (Fig. 18) but there were larger temperature variations ($\pm$ 150°F) on the duct surface when the resistance heaters were used (Fig. 19). Similar variation was seen during the earlier General Dynamics AENFTS testing. As a result, the ignition temperature for the resistance heated simple duct tests depended on which thermocouple was chosen to report the duct temperature. During this program it was felt that the hottest point on the test section was most likely responsible for ignition (when it occurred) and therefore the thermocouple at position 3, which read the highest, was chosen as the reference thermocouple. This position (Fig. 17) was at the mid-point of the duct and at the side with respect to the approach of the ventilation airflow. For convenience, the thermocouple at position 3 was also used in the air heated simple duct, though there was little variation between it and the other 7 available.

The criteria for selecting the reference thermocouple had been different during the General Dynamics testing. During that program, to employ the most conservative interpretation of the data, the thermocouple chosen was the one which consistently read the lowest. The General Dynamics test article consisted of two parallel heated sections of duct. The thermocouple employed was at the mid-point of the upstream duct facing the oncoming ventilation airflow. Other thermocouples were placed backside of the upstream and front and backside of the downstream duct. The variations between this thermocouple and the hottest points observed (normally the backsides of both ducts) ranged from 25°F to 75°F.

While there was no temperature data reported from the General Dynamics test for a thermocouple located at the side of the duct, comparison can be made between the data acquired for this position (position 3) and for the position facing the oncoming flow (position 4) from the present program. It can be concluded (Figure 19) that the General Dynamics MHSIT's would be lower than those obtained in the current program by about 50°F at 1 ft/second and by almost 200°F at 8 ft/second.

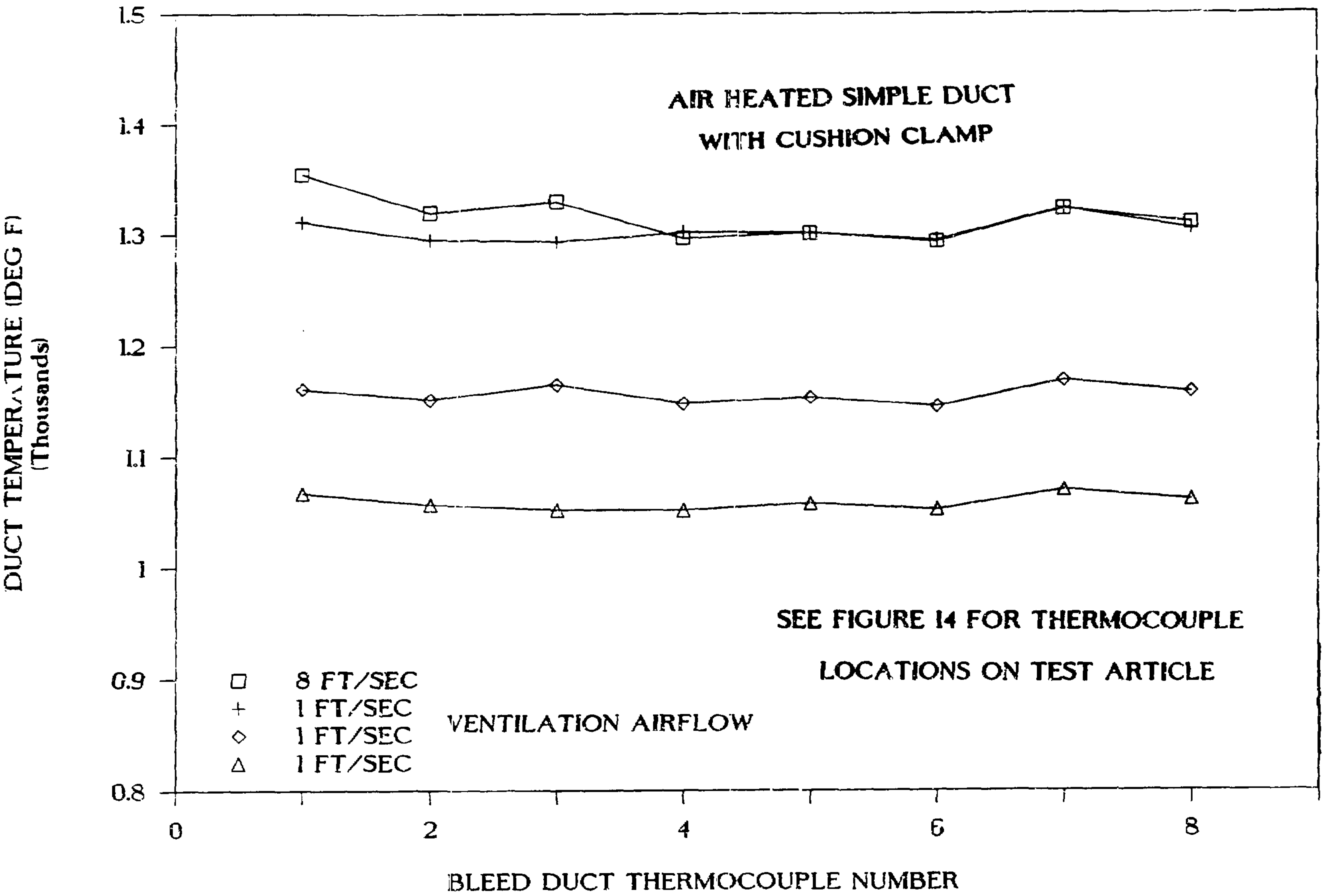


Figure 18. Temperature Variation Along Air-Heated Simple Duct

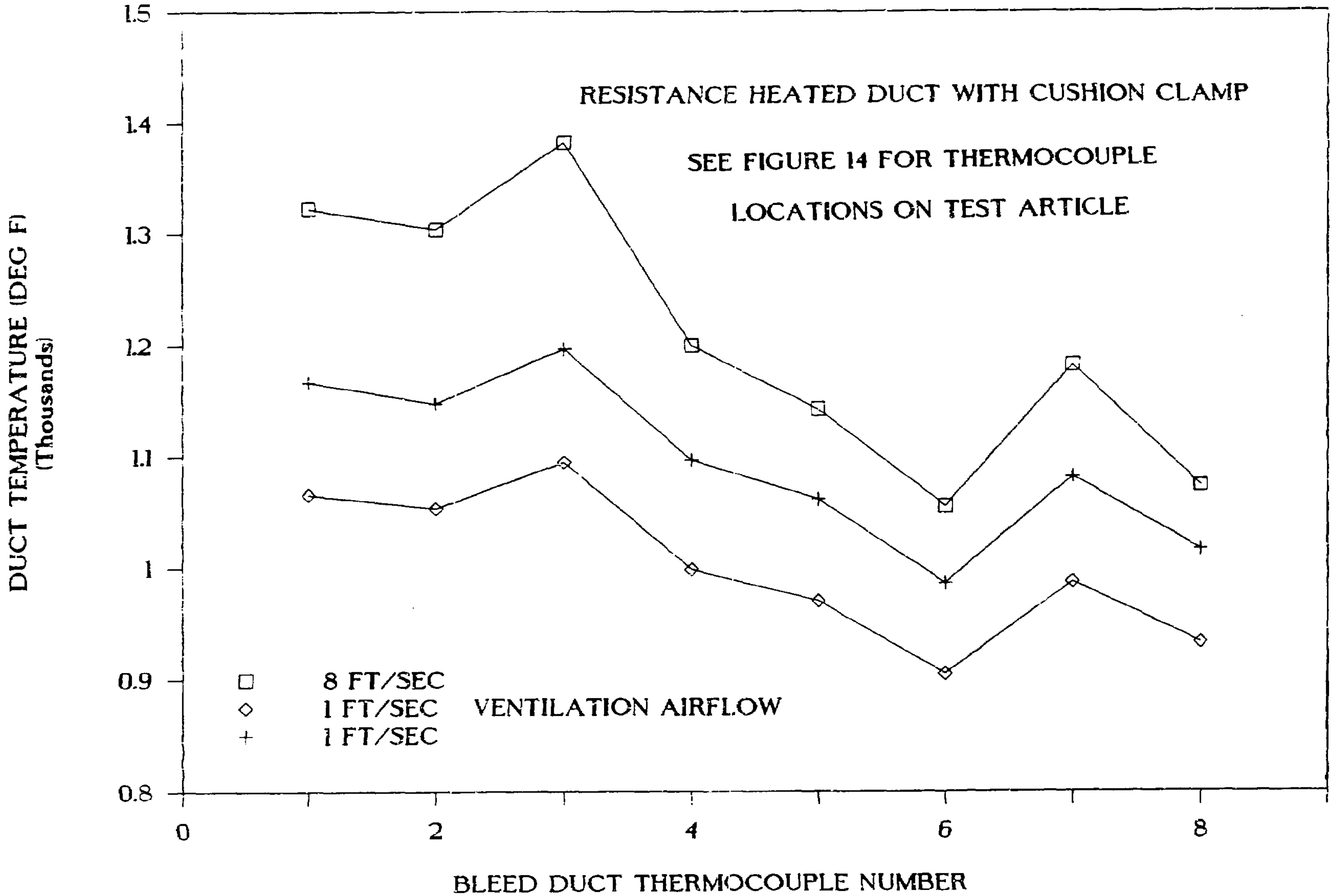


Figure 19. Temperature Variation Along Resistance Heated Simple Duct

An uncertainty analysis of the duct temperature measurement data was made, based on analysis of the hardware installation and test procedures (Appendix B). It was concluded that the duct temperature data would have an uncertainty of $\pm$ 25°F.

The simple duct was mounted for most of its testing in a horizontal position with AENFTS test section also in a horizontal position (Fig. 16). In addition, some of the simple duct testing was performed with the duct and AENFTS test section in a vertical position. The high realism testing was performed with the AENFTS test section in the vertical position. For the simple duct testing the test section was completely free of obstructions such as tanks, piping and ribs. The effect of the presence of a cushion loop clamp on MHSIT was examined during the simple duct tests for both resistance heated and air heated ducts. This was the same clamp that had been used during the General Dynamics testing and was also installed at stream location 5 on the high realism test article. During the simple duct testing it was mounted at the center of the seven inch inconel duct.

Prior to beginning hot surface ignition testing, with the AENFTS test section in the horizontal position, the ventilation air velocity was surveyed using a pitot probe. The pitot probe was installed temporarily, about 0.75 inch upstream and 0.5 inch above the mid point of the simple duct. The ventilation airflow was calibrated to give airflow velocity as a function of measured mass flow for the range of 1 to 10 ft/sec. For the simple duct test, the atmospheric blower was used to supply the ventilation air. The pitot tube was not installed during hot surface ignition testing. This calibration was not repeated with the test section in the vertical position because no significant difference was anticipated.

Spray was the only method of fluid injection used in the simple duct tests. 5606 and JP-4 were sprayed at 8 ml/sec for 5 seconds from a Wagner 621 flat spray nozzle (6 inch spray fan half-width at 12 inches from the spray nozzle exit and a nozzle equivalent diameter of 0.021 inch). The flat spray was parallel to the long axis of the test section and the nozzle was placed 12 inch upstream of the lead edge of the duct. Viewing the simple duct through the rig viewing window, it was clear that the spray completely covered the uninsulated area of the duct. Spray flowrate was controlled by pressurization of the fluid reservoirs and spray flowrate vs. pressure curves for the fluids were generated prior to testing.

The simple duct test section was visible through a quartz window in the AENFTS wall. A video camera was aimed at the test section and made it possible to remotely view injections and ignitions during testing.

2.2.2 High Realism Test Article

Actual F-16 engine nacelle parts were used in the construction of the high realism hot surface ignition test article. Among its principal features were the 13th stage bleed-air duct, air-oil heat exchanger tank, augmentor fuel pump and various tubes and clamps (Fig. 20). The AENFTS was oriented vertically throughout the high realism test so that the position of the F-16 components was the same as if they were installed in the aircraft. The bleed-air duct was made of the same material as the simple duct, 1.5 inch O.D. and 0.036 inch wall thickness inconel tubing. Hot high pressure air was supplied to the duct through the outer wall of the AENFTS test section. Bleed-air traveled from left to right into the augmentor fuel pump and thence into insulated piping to exit the test section. On the actual engine, bleed-air flows through the duct in the same direction though it enters from the engine and it reenters the engine through a perforation at the augmentor fuel pump. Ventilation velocities were measured by a pitot probe installed at a point 1 inch in front of and 1 inch above the most upstream edge of the bleed duct along the center line of the AENFTS (Fig. 20). This position was not directly behind any major obstructions and hence did not represent an abnormally low local ventilation velocity.

Ventilation air was supplied from the facility air storage bottle farm to the high realism test article using the high-pressure, low-flow airflow system except for those test conditions at 11/ft/sec velocity where the

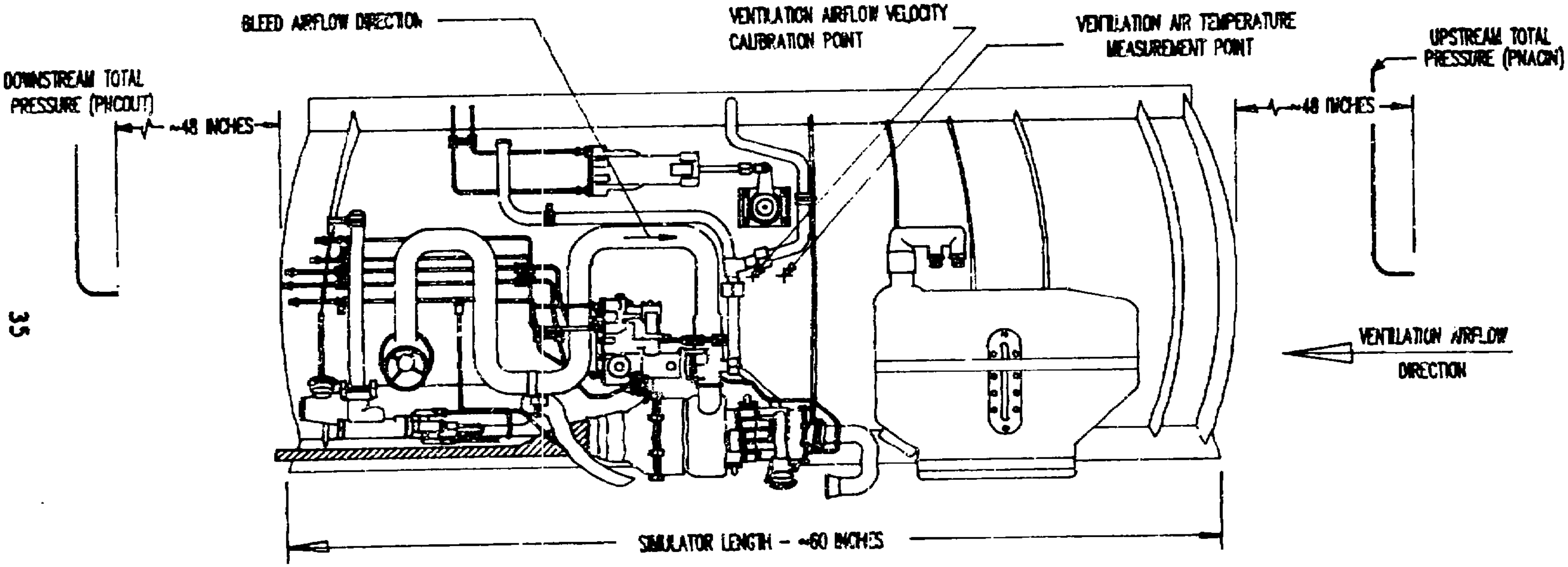


Figure 20. High Realism Test Article

high-pressure high-flow system was employed because the low-flow system would not provide enough airflow to reach this velocity.

The ventilation air temperature was measured by a thermocouple (TAIR-1) suspended in the ventilation air stream about halfway between the nacelle side wall and the engine side wall. The thermocouple was located about 4 inches upstream of the most upstream edge of the bleed duct on the centerline of the test section (Figures 20 and 21). A standard commercial 1/8 inch stainless steel sheathed thermocouple assembly was employed. A shield, constructed from 1/2 inch diameter 0.008 wall stainless steel tubing, was placed between the thermocouple and the hot bleed duct to shield the thermocouple from radiation from the bleed duct. The tubing was cut away around the thermocouple bead to allow it to be fully immersed in the airflow and only a flap extended above the bead. The outside of the shield tubing was covered with fiberfax insulation to minimize its heating from the bleed duct radiation.

A pressure transducer (PNACIN) was used to measure the ventilation air pressure. This transducer was installed in the AENFTS about 6 feet upstream of the test article (Fig. 20).

Due to the effect of the various clamps and obstructions in the high realism test article it was anticipated that hot surface ignition conditions would be different at different locations on the bleed-air duct. For this reason a total of six stream and two spray fluid injection locations were used in the high realism test phase (Fig. 21). The spray injection method used the same nozzle used in the simple duct tests, a Wagner 621 flat spray nozzle, placed either upstream or downstream of the bleed duct. When the spray came from downstream, the nozzle was placed six inches downstream of the aft end of the bleed duct. When the spray came from upstream, the nozzle was placed six inches upstream of the its upstream end. For both positions, the nozzle was located on the test section centerline and the spray fan was aligned along the duct. Preliminary tests made with the viewing window removed and the duct unheated indicated that spray from either direction thoroughly wetted the entire bleed duct. No attempt was made to determine to what degree the

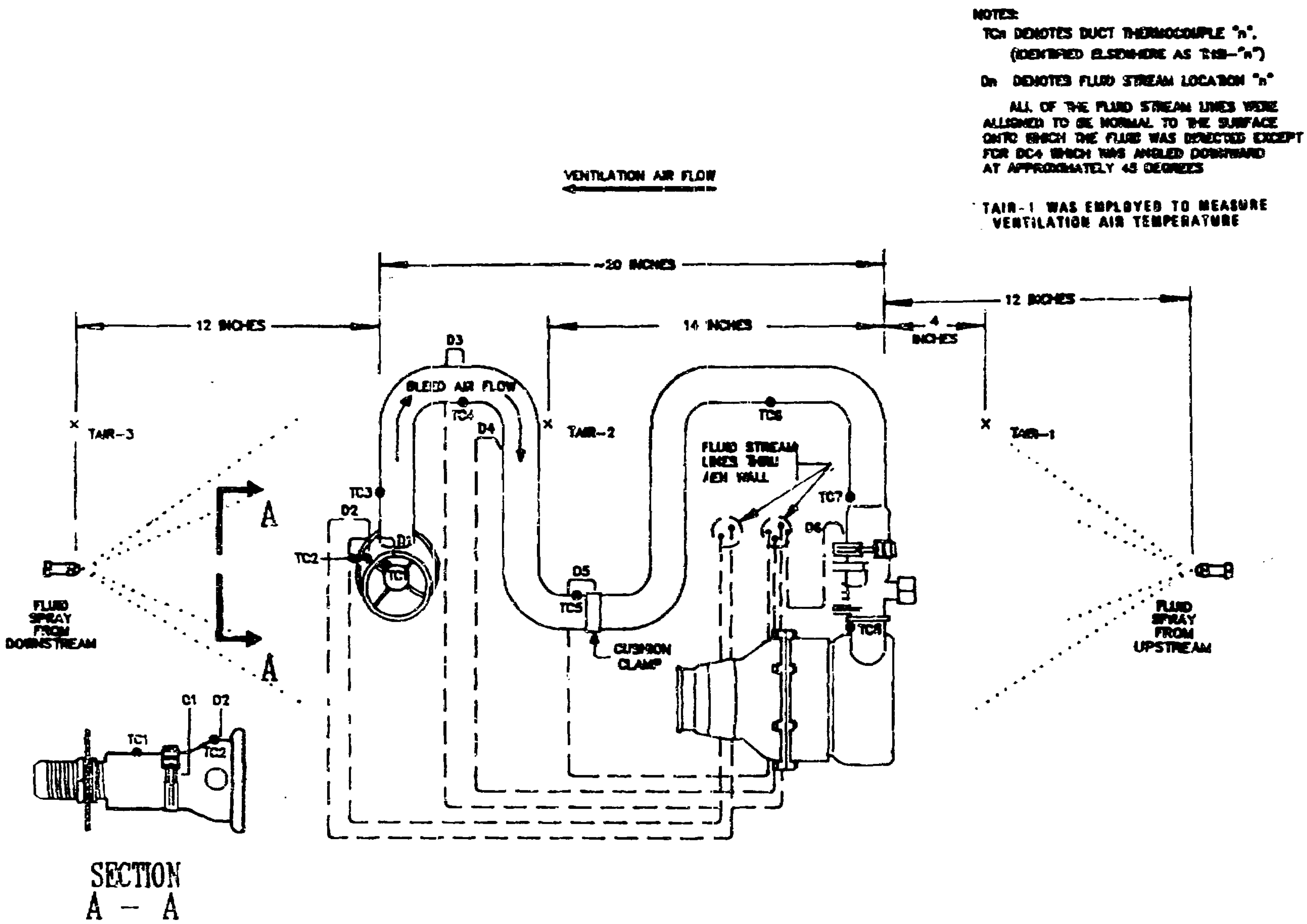


Figure 21. Fluid Injection and Thermocouple Locations on High-Realism Test Article

ventilation airflow reduced this though the occurrence of ignitions at all velocities demonstrated that fluid continued to strike some part of the duct at all velocities. The fluids were generally sprayed at 8 ml/sec for 5 seconds.

There were six fluid stream locations. Fluid traveled from the fluid reservoir where it was maintained at 100 psig through a micrometering valve and then through one of six stainless steel tubes (0.070 inch I.D.) to the stream location. The fluids streams were generally supplied at 2 ml/sec for 10 seconds through the stream tubes. This flowrate produced a solid stream of fluid out of the injection tube. The effect of ventilation airflow velocity on the streams of fluid's ability to reach the duct was not investigated but the momentum of the streams and the narrow gaps (0.5 inch) between the stream tubes and the bleed duct made any change caused by velocity unlikely. All tubes ended normal to the bleed duct surface except for location 4 which was angled forward and downward at 45° (Fig. 21). The stainless steel tubes were routed along the engine side of the test article, as far as possible from the hot bleed duct. After each fluid stream injection, compressed air was blown through the stainless steel tube so that the next stream injection would use fluid at nacelle room temperature, rather than uncontrollably heated fluid in the stainless steel tube.

Eight type K thermocouples were also tack-welded along the bleed-air duct (Fig. 21) of the high realism test article. A plot of duct temperature at the various thermocouple locations is shown in Figure 22. The bleed duct thermocouples were generally associated with fluid injection locations and the MHSIT is reported by using the associated thermocouple temperature for the stream injection location:

Stream location 1: The fluid was introduced onto a Marmon clamp that joined the bleed duct to the bleed-air penetration fitting on the nacelle side of the AENFTS. The associated thermocouple, THSI-1, was tack-welded to the thick walled fitting. As the test progressed, it was found that due to the thickness of the fitting, the surface temperature of the fitting was relatively low and the temperature response was extremely

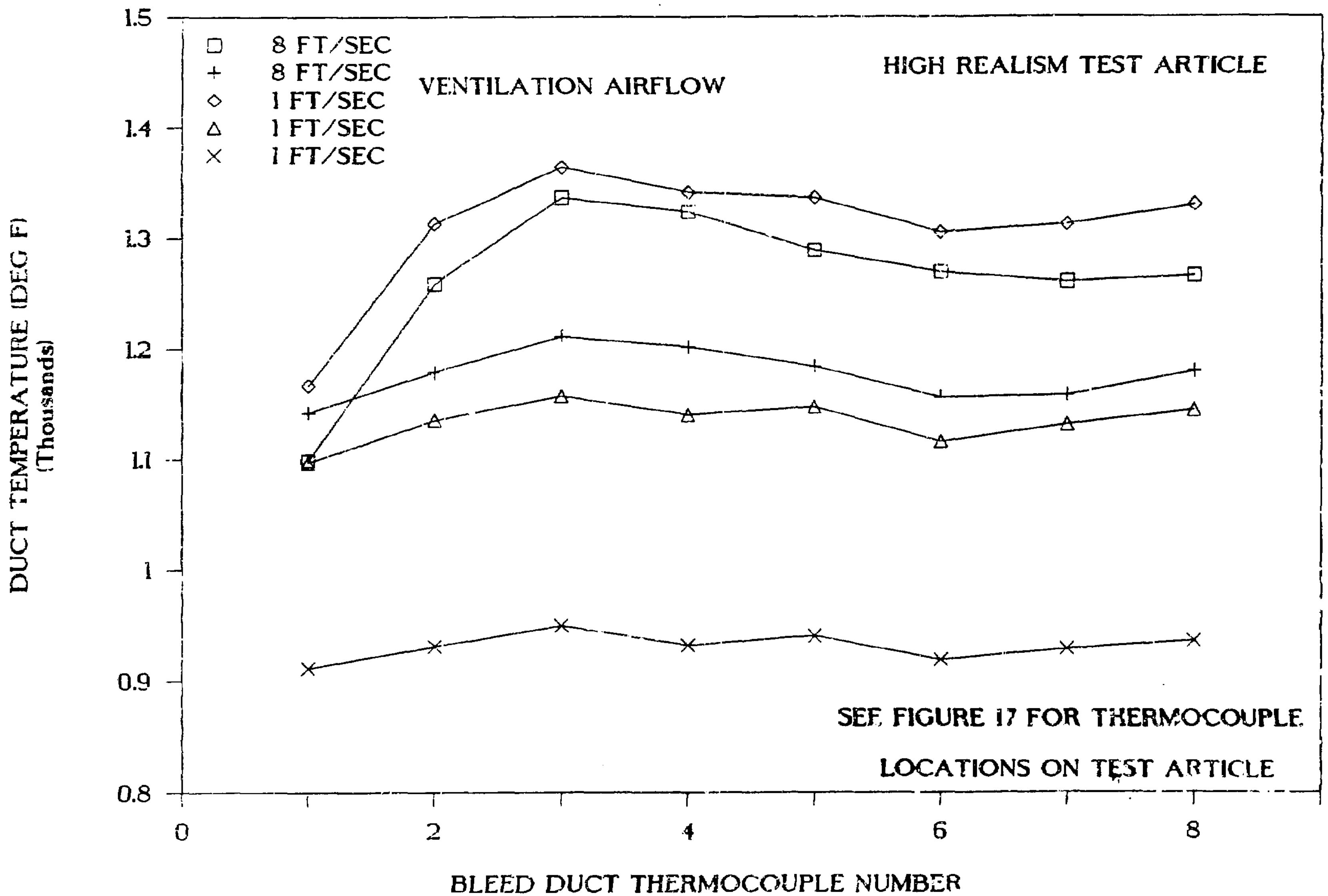


Figure 22. Temperature Variation Along High-Realism Duct

slow. Since the injection location was the least realistic and did not exist in an actual F-16 nacelle, testing at this location was terminated.

Stream location 2: The fluid was introduced onto the bell shaped inlet to the Inconel bleed duct. THSI-2 was attached to the bell shaped inlet as well. THSI-3, tack-welded to the bleed duct several inches above bell-shaped inlet, was not associated with any stream location. It was employed reference duct temperature thermocouple throughout the test since it was the hottest location. It was also used to report the MHSIT for spray since a fluid spray was location non-specific and it was felt that the hottest location on the duct most accurately represented the ignition temperature for spray injection.

Stream location 3: The fluid was introduced onto the top of a horizontal section of bare duct. THSI-4, tack-welded to the underside of the duct at the same location was the associated thermocouple.

Stream location 4: The fluid was introduced onto the aft (downstream) face of a vertical section of bare duct. THSI-4 was the thermocouple closest to this location also.

Stream location 5: The fluid was introduced onto a horizontal duct portion of the duct at the point where the the cushion clamp was installed. THSI-5 was tack-welded just upstream of the clamp. THSI-6 was tack-welded to the bottom of the following bend, a location similar to THSI-5 but lacking the clamp and was not associated with any stream injection location.

Stream location 6: The fluid was introduced onto a Marmon clamp between the bleed duct and the augmentor fuel pump controller butterfly valve. THSI-7 was located on the duct upstream of the change in duct diameters for this clamp. THSI-8 was tack-welded to the inlet of the augmentor fuel pump just downstream of the stream tube.

Three different video cameras were used to view the high realism test article during testing (Fig. 23). It was possible to detect that ignition

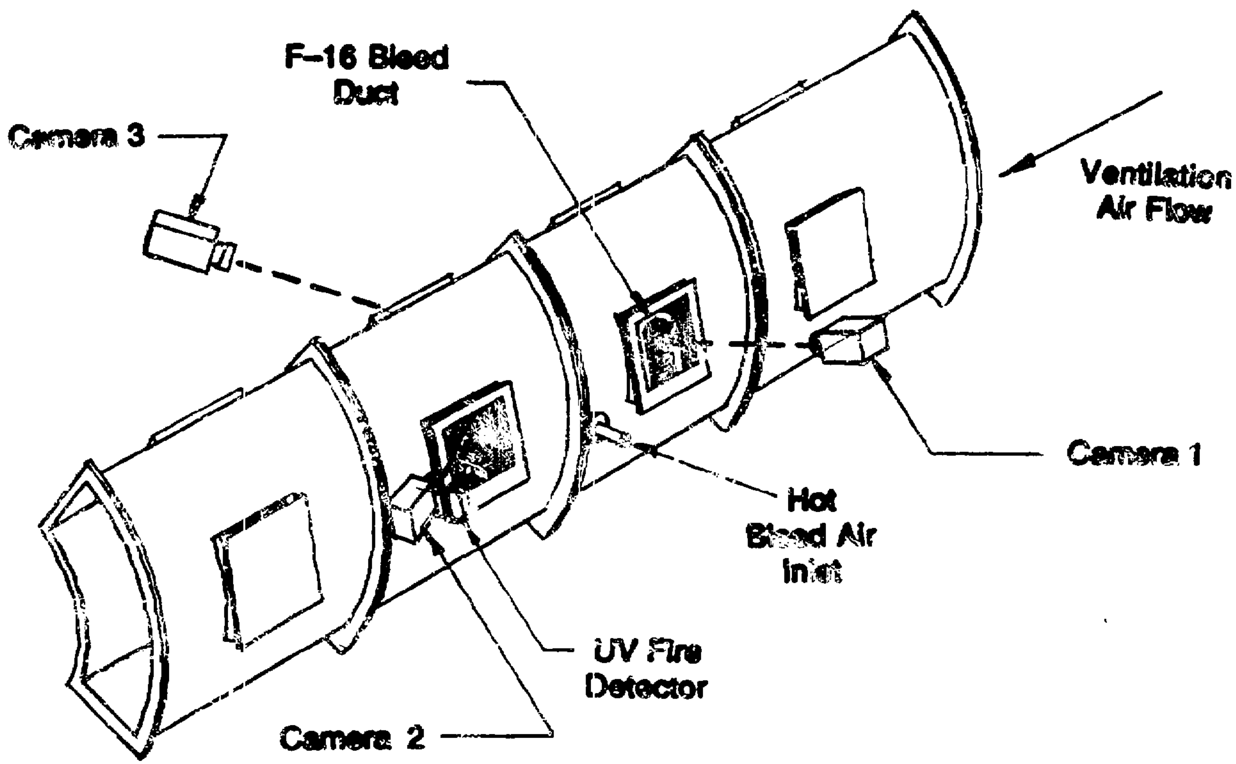


Figure 23. Video Camera Placement

had occurred but not all parts of the the bleed duct were visible and it was not possible to determine the exact ignition location. Also assisting in the detection of a fire was an ultraviolet fire detector made by Graviner, Ltd. (Ref. 9). This detector was mounted next to the video camera placed in the test section side window downstream of the bleed duct where it consistently detected the presence of fires in the test secion. Another camera viewed the bleed duct through a test section side window on the upstream side of the high realism test article. The third camera viewed the inside of the AENFTS through an edge window on the top of the test section. These three cameras and the UV detector made it possible to determine whether or not there was ignition from the control room.

Extensive leak checks were performed on the high realism test article in order to ensure that no bleed-air would leak from the bleed-air duct and alter the normal ventilation airflow patterns and change local ventilation velocities. To ensure that there were no leaks in the bleed duct installation, the duct was pressurized with cold and hot air, smoke generators were employed and visual checks were made with yarn tufts.

2.3 Data Collection and Reduction

Critical variables in this test were the duct temperature (THSI-1 through THSI-8), ventilation air velocity, ventilation air temperature (TAIR-1), ventilation air pressure (PNACIN) and test fluid type, injection method, flowrate and duration of injection. Duct temperatures and ventilation air conditions were logged to disk on the facility computer while test fluid variables were set prior to the test and were logged on a hand log data sheet. The computer acquired data was logged just before the injection of the test fluid, and the MHSIT measured in this test program was an initial duct temperature and not the temperature of the duct at the time of ignition. This does not compromise the value of the test data, however, as this initial temperature is comparable to the engine compartment temperatures which can be specified by an aircraft designer.

Duct temperature vs. time data for selected simple duct tests were acquired using a Honeywell Visicorder strip chart recorder. Figure 24

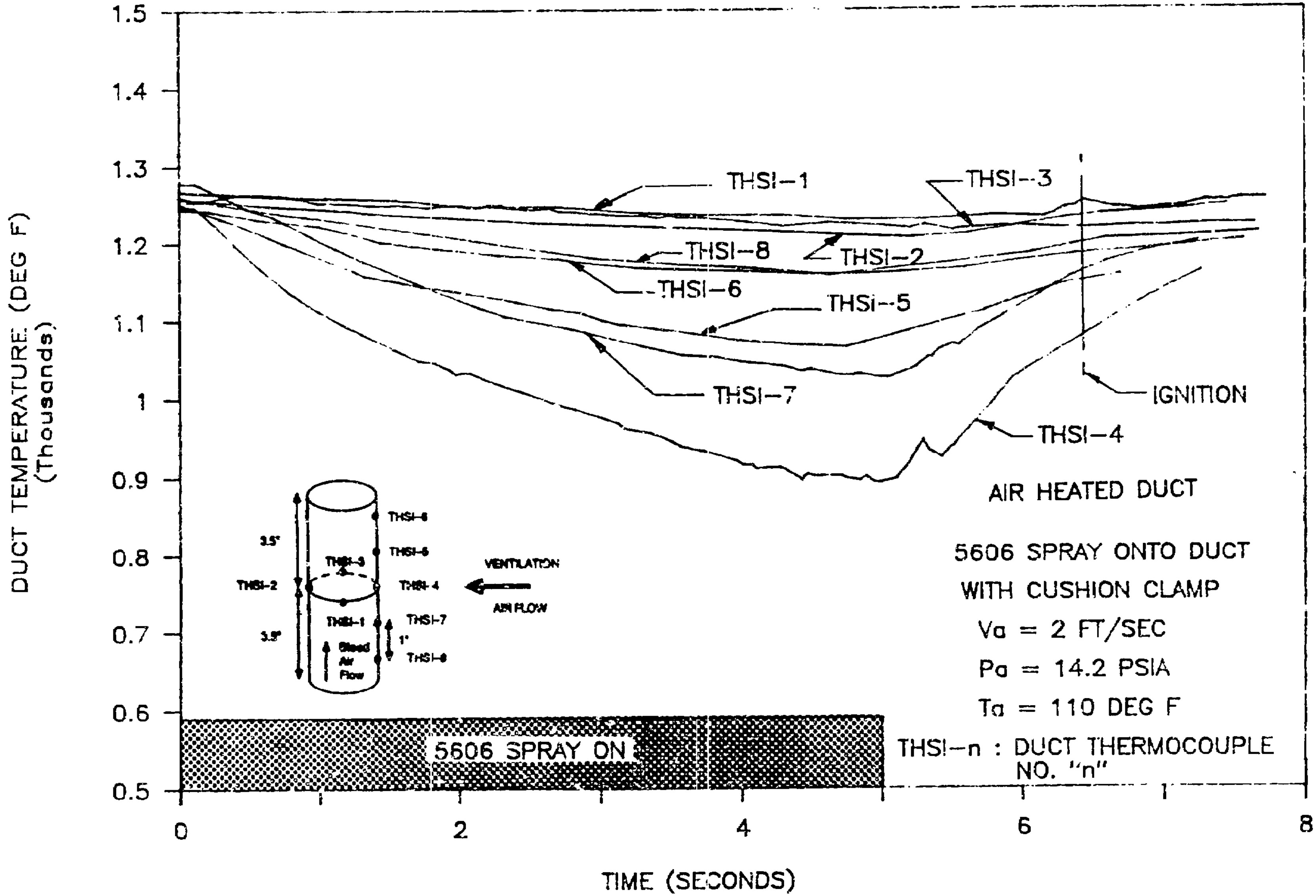


Figure 24. Duct Temperature Variation With Time During Simple Duct Test

shows the temperature data recorded for each of the 8 duct thermocouples during the 5 seconds when 5606 was being sprayed onto the duct, during the next 1.5 second when the hot air was bringing the duct back up to temperature and briefly following ignition (the point of ignition having been determined from visual observation of the test along with review of the video tape record following the test). The th rmocouples most directly in the path of the spray, those at positions 4, 5 and 7, show the greatest temperature reduction during the 5 seconds of 5606 spray and those on the sides and back face of the duct are relatively unaffected by the spray.

Also logged by hand was whether or not there was ignition, the ignition time delay (time elapsed between beginning of injection and the ignition of the fluid) and the video tape time, a record of the location of the test on the tape. A closed circuit TV camera with a zoom lens was mounted on a tilt and pan mechanism on the top of the fuel cart. During fire tests, the camera was focused on the viewing window in the test section adjacent to the test fire zone. Its output signal was observed on a TV monitor on the AENFTS control panel to allow the test operator to observe ignitions and assure safe conduct of the test. A video cassette recorder (VCR) received and recorded the signal from the TV camera. The video of the simple duct tests would show the spray injection pattern, smoke formation and the ignition of the fluid. The video tape of the high realism tests only revealed the reflection of the occurrence of a fire, the view being almost completely obstructed by the tanks and ribs in the F-16 simulator.

The video system was fairly low speed (30 frames/second, 2 fields/frame) and ignitions occurred too fast to make precise visual observations of the beginning of ignition. The video tape did provide a backup of the ignition delay timer.

Ignition delay time was measured by the fluid injection system timer that started when an electrical signal was sent to the injection system ball valve and ended when the UV fire detector unit detected a fire or the test operator observed a fire on the video displays and pressed a switch.

These were subsequently manually corrected for the delay between the signal being sent to the ball valve and the fluid's first contact with the duct based on earlier manual calibration for each drip location. These ignition delay data are tabulated in Appendix A.

AENFTS test data consisted of temperatures and pressures which were measured by thermocouples and pressure transducers in the test cell and sampled, digitized, averaged and calibrated by the facility computer system (Fig. 25). Lists of the temperature variable names and ModComp data channels (Table 1) and the pressure variable names and data channels (Table 2) are included in this section. These millivolt values were converted to engineering unit data for the temperature and pressure at the AENFTS flowmeters and used to calculate flowrates and ventilation velocities in the test section. The airflow equations for the venturis are based on the Compressed Gas Handbook (Ref. 10) and those for the sonic nozzles are based on data from their manufacturer. This information was immediately used to update the AENFTS display terminals (approximately once every 10 seconds) and by activating a data log switch the operator could send this data to a line printer and also log it on disk. The AENFTS facility computer is a 16 bit, general purpose digital computer for real time multi-programming applications with 64K RAM memory manufactured by Modular Computer Systems Inc. (ModComp) of Ft. Lauderdale, Fl.

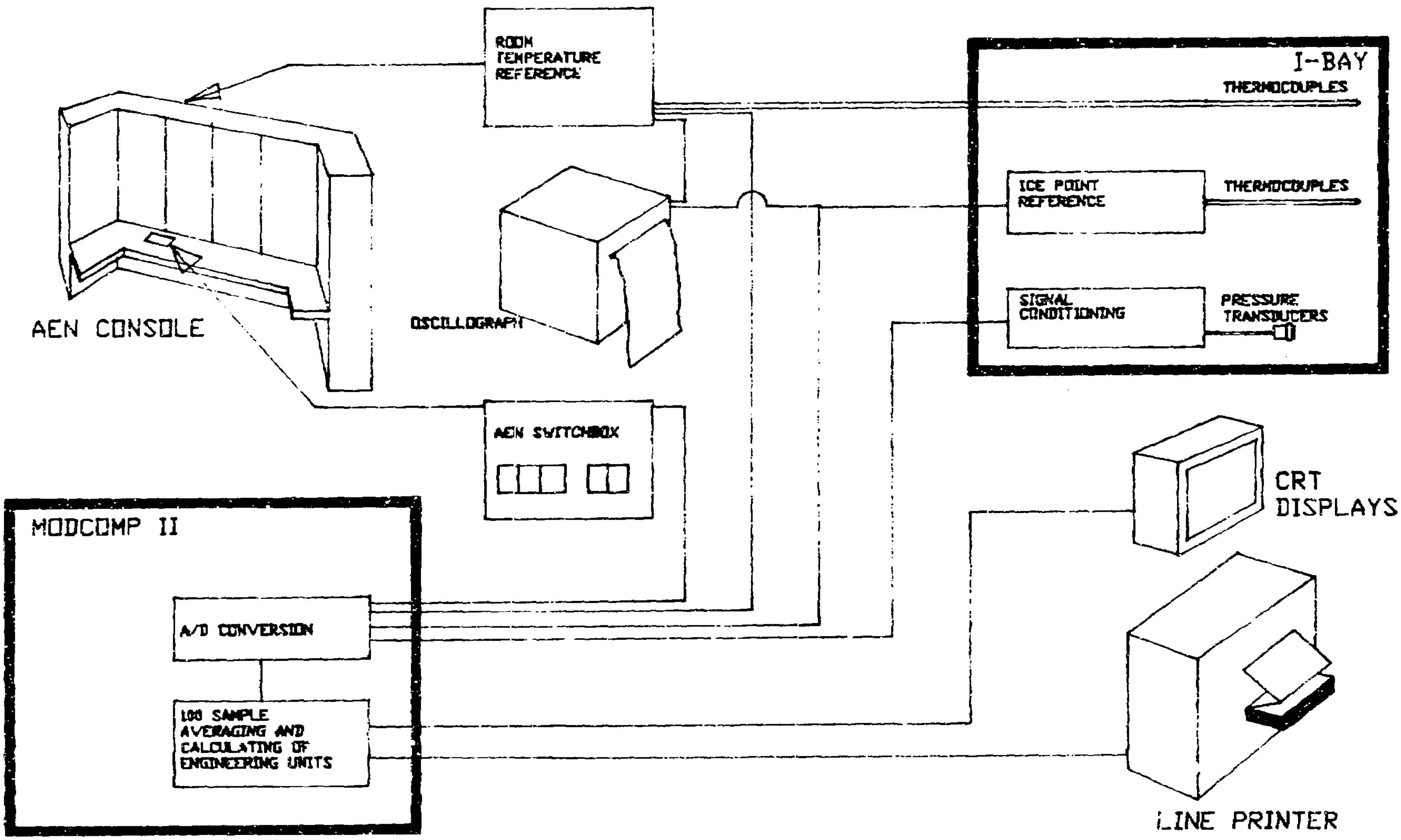


Figure 25. Schematic Diagram of Computer Data Acquisition System

Table 1. AENFTS Temperature Instrumentation

THERMOCOUPLE NUMBER	MODCOMP CHANNEL	SOFTWARE SYMBOL	DESCRIPTION	TYPE	ACCURACY
TC-28	1	TENG1A	Engine side skin temp zone 1	K	± 4 degrees F.
TC-29	2	TENG1B	Engine side skin temp zone 1		
TC-30	3	TENG2A	Engine side skin temp zone 2		
TC-31	4	TENG2B	Engine side skin temp zone 2		
TC-32	5	TENG3A	Engine side skin temp zone 3		
TC-33	6	TENG3B	Engine side skin temp zone 3		
TC-34	7	TENG4A	Engine side skin temp zone 4		
TC-35	8	TENG4B	Engine side skin temp zone 4		
TC-36	9	TENG5A	Engine side skin temp zone 5		
TC-37	10	TENG5B	Engine side skin temp zone 5		
TC-38	11	TENG6A	Engine side skin temp zone 6		
TC-39	12	TENG6B	Engine side skin temp zone 6		
TC-40	13	TAIR-1	Nacelle air temp zone 1		
TC-41	14	TAIR-2	Nacelle air temp zone 2		
TC-42	15	TAIR-3	Nacelle air temp zone 3		
TC-43	16	TAIR-4	Nacelle air temp zone 4		
TC-44	17	TAIR-5	Nacelle air temp zone 5		
TC-45	18	TAIR-6	Nacelle air temp zone 6		
TC-46	19	TNAC1A	Nacelle side skin temp zone 1		
TC-47	20	TNAC1B	Nacelle side skin temp zone 1		
TC-48	21	TNAC2A	Nacelle side skin temp zone 2		
TC-49	22	TNAC2B	Nacelle side skin temp zone 2		
TC-50	23	TNAC3A	Nacelle side skin temp zone 3		
TC-51	24	TNAC3B	Nacelle side skin temp zone 3		
TC-1	105	THSI-1	Test article temp #1		
TC-2	106	THSI-2	Test article temp #2		
TC-3	107	THSI-3	Test article temp #3		
TC-4	108	THSI-4	Test article temp #4		
TC-5	109	THSI-5	Test article temp #5		
TC-6	110	THSI-6	Test article temp #6		
TC-7	111	THSI-7	Test article temp #7		
TC-8	112	THSI-8	Test article temp #8		
TC-58	31	TOUTLG	Nacelle outlet air temp (long)		
TC-59	32	TOUTSH	Nacelle outlet air temp (short)		
TC-60	33	TNACIN	Nacelle inlet air temp	K	
TC-61	34	TBL-08	Low flow venturi temp	T	
TC-62	35	TBL-24	Blower outlet temp	K	
TC-63	35	T-NIFL	Hi flo/Hi press temp		
TC-64	37	TSTKLO	Lower exhaust stack temp		
TC-65	38	TSTKUP	Upper exhaust stack temp		
TC-70	39	OATPAD	Pad outside air temp		
	40	OAT-RF	Roof outside air temp		
	41	TNACRM	Nacelle room air temp		
	43	T-NPAD	North pad temp	K	
	44	RTDREF	Reference room temp	T	
TC-72	45	TGLYCO	Cold glycol temp	J	
TC-74	47	T--HYD	Hyd. reservoir temp	J	
TC-75	46	T-FUEL	Fuel injection reservoir temp	J	
TC-91	94	TLOFLO	Lo flo/Hi press temp	T	
TC-201	97	TBHOUT	Bleed htr. outlet tem	K	
TC-202	99	TBHNAI	Bleed air temp at nacelle inlet	K	
TC-205	98	TBHNOZ	Bleed air nozzle inlet temp	K	± 4 degrees F

Table 2. AE NFTS Pressure Instrumentation

PRESSURE NUMBER	MODCOMP CHANNEL	SOFTWARE SYMBOL	ITEM DESCRIPTION	MFG&S/N	RANGE	ACCURACY*
PT-1	57	PBLOUT	Blower outlet press	S-34212	0-50 in. H_2O	±0.25
PT-2	69	DPVENT	24" venturi delta P	S-33659	0-60 in. H_2O	±0.5
PT-4	59	PNACIN	AEN inlet press	S-34214	0-30 psia	±0.25
PT-5	60	PEXFAN	Scrubber inlet press	S-27984	0-16 in. H_2O	±0.25
PT-6	61	PHIFLO	Hi press/hi flow nozzle press		0-1000 psia	±0.25
PT-7	62	PLOFLO	Hi press/lo flow nozzle press		0-640 psia	±0.25
PT-8	63	PEJFLO	Ejector nozzle press		0-500 psia	±0.25
PT-9	64	PNCOUT	AEN outlet press		0-30 psig	±0.25
PT-10	65	P-STOR	High press line press		0-2500 psig	±0.25
PT-11	66	P-FUEL	Fuel reservoir press	S-34218	0-420 psig	±0.5
PT-12	67	P--HYD	Hydraulic reservoir		0-5000 psig	±0.25
PT-13	68	PBAROM	Barometric press	S-40737	26-32 in.Hg	±0.25
PT-14	78	PNZFUL	Fuel nozzle press	S-48291	0-500 psig	±0.25
PT-15	77	PNZHYD	Hydraulic fluid nozzle press		0-5000 psig	±0.25
PT-16	79	PLFLIN	8" venturi inlet press	S-50823	±1.5 psig	±0.1
PT-17	51	DPUM-4	8" venturi delta P	M-21784-1	0-4 in. H_2O	±0.15
PT-18	50	DPVN40	8" venturi delta P	M-21784-2	0-40 in. H_2O	±0.15
PT-19	114	PBHNOI	Bleed htr. nozzle inlet pressure	ST-67772	0-1000 psia	±0.25
PT-20	115	PBHNAI	Bleed htr. inlet press	ST-67774	0-500 psia	±0.25
PT-21	113	PBH-IN	Bleed air press @ nacelle inlet	ST-67773	0-500 psia	±0.25
PT-22		PHALON	Halon dump tank press			±0.25

*Percent of full scale reading

Manufacturers: S: Sensotec
M: MKS
ST: Setra

3.0 TEST PROCEDURE

A standard test procedure was followed throughout the hot surface ignition test program.

1. The ModComp computer data acquisition system was started enabling real time monitoring and logging to disk of hot surface ignition variables such as duct temperatures, ventilation velocity, ventilation air temperature and ventilation air pressure.

2. The video system was started allowing visual observation, from the control room, of fluid injections and ignitions (including the fire warning light triggered by the UV fire detector) in the AENFTS as well as video taping of the hot surface ignition test.

3. The test fluid was prepared. Injection method, flowrate, injection duration and fluid type are selected at this point.

4. Ventilation air conditions including velocity, temperature and pressure were established.

5. The test article was heated to the planned test temperature. Either electrical resistance heaters or 1 lb/sec air from the bleed-air heating system was used to heat the simple duct and only hot air was used to heat the high realism bleed-air duct.

At the beginning of the day, approximately 1 hour was required to heat the duct to test temperatures. Between injections, however, reasonable steady temperature conditions were reached in 2 to 5 minutes.

6. At this time, the ModComp data displays were checked to ensure test conditions were met. Next, data was logged to the ModComp disk, the video tape machine was started and the fluid was injected. The video displays were observed for injection of the fluid and ignition.

In this test program, the duct temperature was started from a high temperature and was lowered as ignitions were obtained. Once the duct temperature was high enough to ignite the test fluid, the duct temperature was reduced 50°F and the fluid was reinjected with all other variables such as ventilation velocity, fluid flowrate, etc. held constant. This process was repeated until ignition did not occur. Two additional injections were then performed at that duct temperature. When a bleed duct temperature was reached at which three tests could be conducted without ignition occurring, testing at those ventilation air conditions and test fluid conditions considered to be completed.

<u>THE MINIMUM HOT SURFACE IGNITION TEMPERATURE (MHSIT) WAS THEN DEFINED TO BE THE LOWEST BLEED DUCT TEMPERATURE THAT HAD PRODUCED IGNITION. BECAUSE THIS TEMPERATURE WAS GENERALLY 50°F ABOVE THE TEMPERATURE WHERE 3 TESTS WITHOUT IGNITION HAD OCCURRED AND THE DUCT THERMOCOUPLE TEMPERATURE MEASUREMENT ERROR WAS ESTIMATED TO BE ±25°F (SECTION 2.2.1), THE UNCERTAINTY OF THIS MEASUREMENT (MSHIT) WAS CONSIDERED TO BE +25°F AND -75°F.</u> Ventilation air variables were normally held constant for 30 seconds at the end of each injection to ensure that there would be no ignition in that particular test. This allowed for any normal ignition delays. Data from a typical series of these tests (83282 stream onto high realism test article at location 3, duct temperature measured at location 5, variation is velocity) is shown in Figure 26.

At the completion of a day of testing, test data on the hand log data sheets and ModComp disk were combined. It was then possible to plot fire/no fire data using duct temperature on the Y-axis and ventilation air velocity (or temperature or pressure) on the X-axis as shown in Figure 26. The symbols used in this plot are plus sign for ignition, and an open square for no ignition.

Data of this type are presented in Appendix A for all the tests conducted in this program. Ignition delay data are also tabulated in Appendix A.

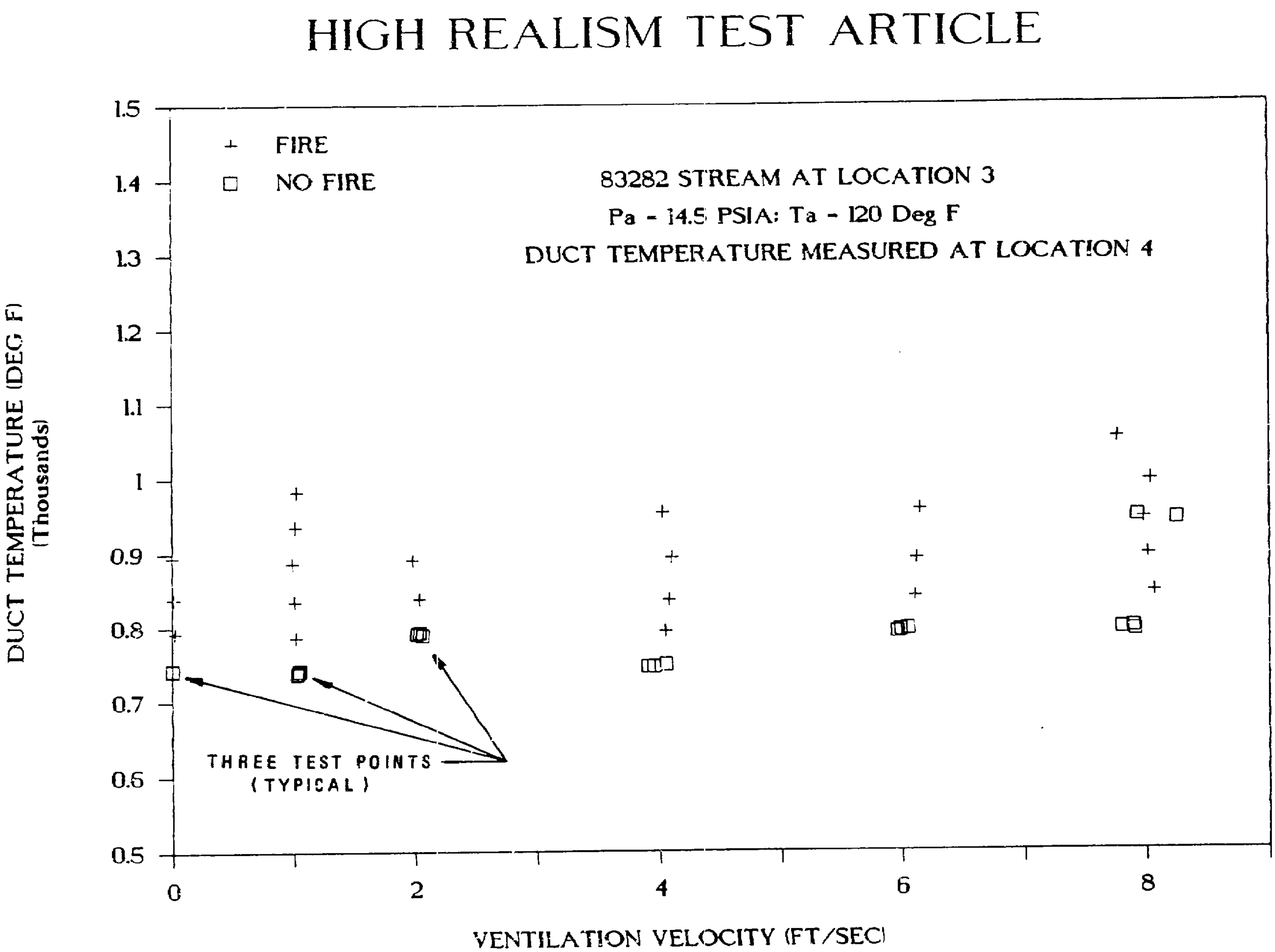


Figure 26. Sample Plot of Fire/No Fire Test Data

For this test program, the minimum hot surface ignition temperature (MHSIT) is defined as the lowest temperature to produce ignition that was above the temperature where three tests occurred without ignition. For example, at 2 ft/sec on Figure 26, the MHSIT was approximately 850°F. MHSIT data for the five test fluids was obtained in this way throughout the test program.

4.0 TEST RESULTS

4.1 Simple Duct Tests

All simple duct tests were performed prior to installing the high realism test article. The simple duct tests enabled comparison to past data and the study of hot surface ignition test data in a uncomplicated environment. In the clean AENFTS test section the ventilation velocity was measured and assumed to be uniform at the duct compared to the obstruction filled high realism test article which would have areas with velocity both above and below the average. The simple duct was also visible through an AENFTS window and spray patterns, nacelle ventilation flow patterns and ignitions were directly observable.

A test matrix (Table 3), summarizes the three groups of simple duct tests that were performed during this program. Two airplane fluids, JP-4 and 5606 were sprayed on the simple duct from upstream in the test section at 8 ml/sec for 5 seconds. Ventilation air pressure and temperature were held as constant as possible at 14.4 psia and 120°F, respectively. Ventilation air velocity was varied from 0 to 8 ft/sec.

The Simple Duct tests were organized into three groups in the test matrix. The majority of the tests were performed in the first two groups, (1) the effect of the cushion loop clamp and (2) the effect of the duct heating method on the MHSIT. A cushion loop clamp was placed on the simple duct where it was contacted by the fluid spray so that the effect of such a device (acting as a flow obstruction and/or fuel vapor trap) on MHSIT could be evaluated. The simple duct was built so that it could be heated either with electrical resistance heaters or with hot-air at 1 lb/sec from the AENFTS bleed-air heating system.

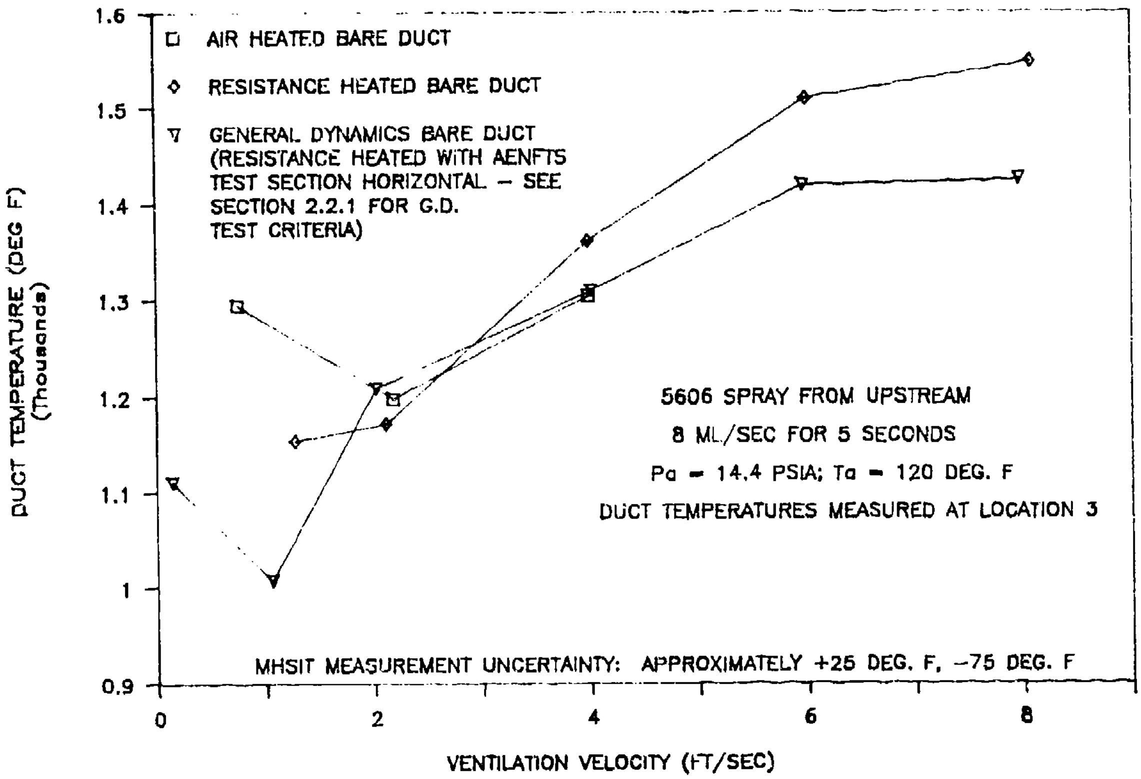
All four configurations for the simple duct (air or resistance heating, bare duct or duct with clamp) were tested with both JP-4 and 5606. The results of these tests are shown in Figures 27, 28, 29 and 30 and summarized in Table 4. For these tests, the AENFTS test section was

Table 3. Simple Duct Test Matrix

(All tests employed spray from upsteam at duct centerline)

TEST CONDITION	CONDITIONS OF VENTILATION AIR			FLUIDS	
	Pressure (psia)	Temperature (deg. F)	Velocity (ft/sec)	JP-4	5606
EFFECT OF THE PRESENCE OF CLAMP ON MHSIT - GROUP 1					
(1) Bare Duct	14.4	120	1 - 8	X	X
(2) Duct with Clamp	14.4	120	1 - 8	X	X
8ml/sec spray for 5 sec					
air heated and resistance heated					
horizontal nacelle/duct					
EFFECT OF THE DUCT HEATING METHOD ON MHSIT - GROUP 2					
Same tests as above:					
(1) Resistance Heated	14.4	120	1 - 8	X	X
(2) Air Heated	14.4	120	1 - 8	X	X
8ml/sec spray for 5 sec					
with and without clamp					
horizontal nacelle/duct					
EFFECT OF NACELLE/DUCT ORIENTATION ON MHSIT - GROUP 3					
(2) Horizontal Nacelle/Duct (same tests as above)	14.4	120	1 - 8		X
(3) Vertical Nacelle/Duct: Test Section Rotated	14.4	120	1 - 8		X
8ml/sec spray for 5 sec					
bare duct					
air heated					

BARE BLEED DUCT



DUCT WITH CUSHION CLAMP

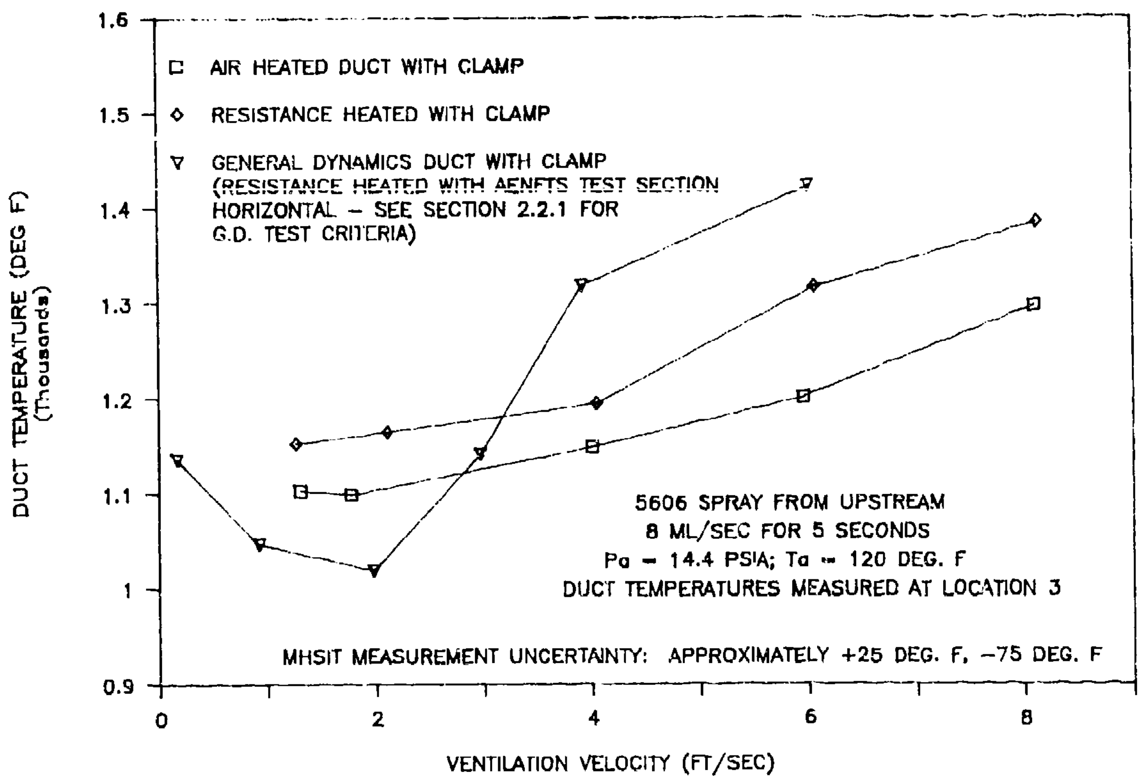
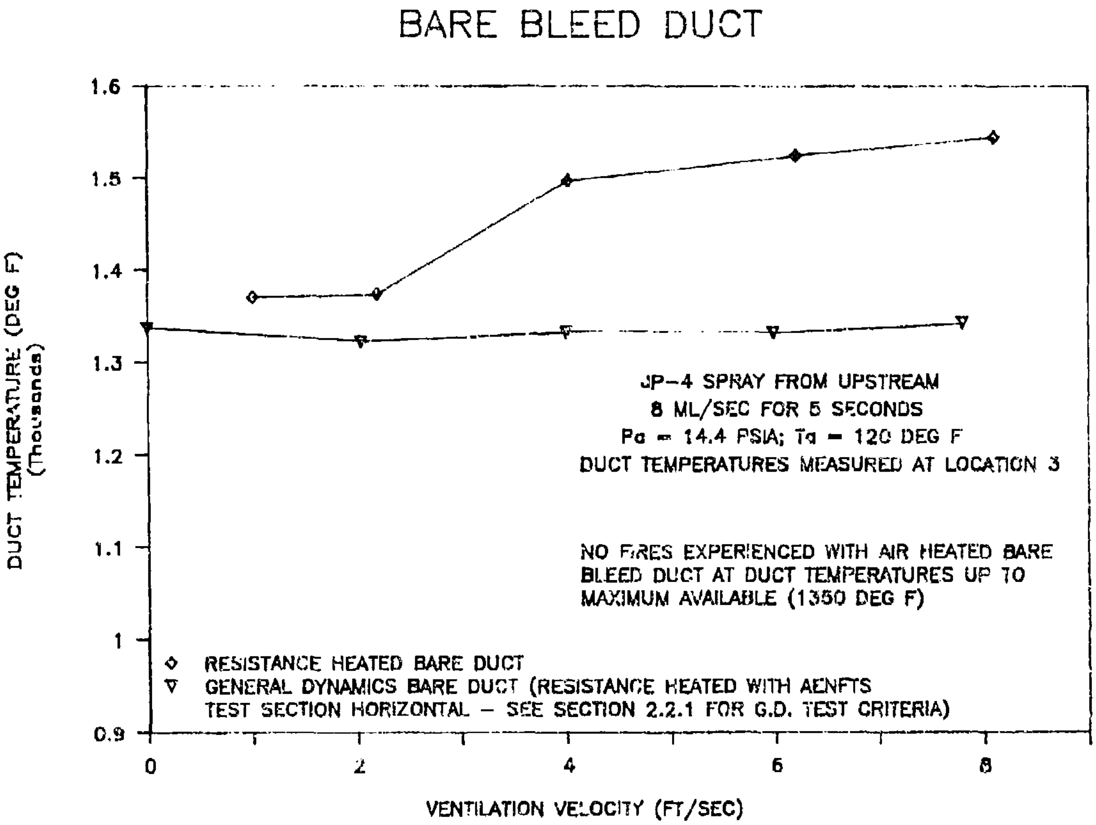


Figure 27. Effect of V_a on Simple Duct MHSIT for 5606



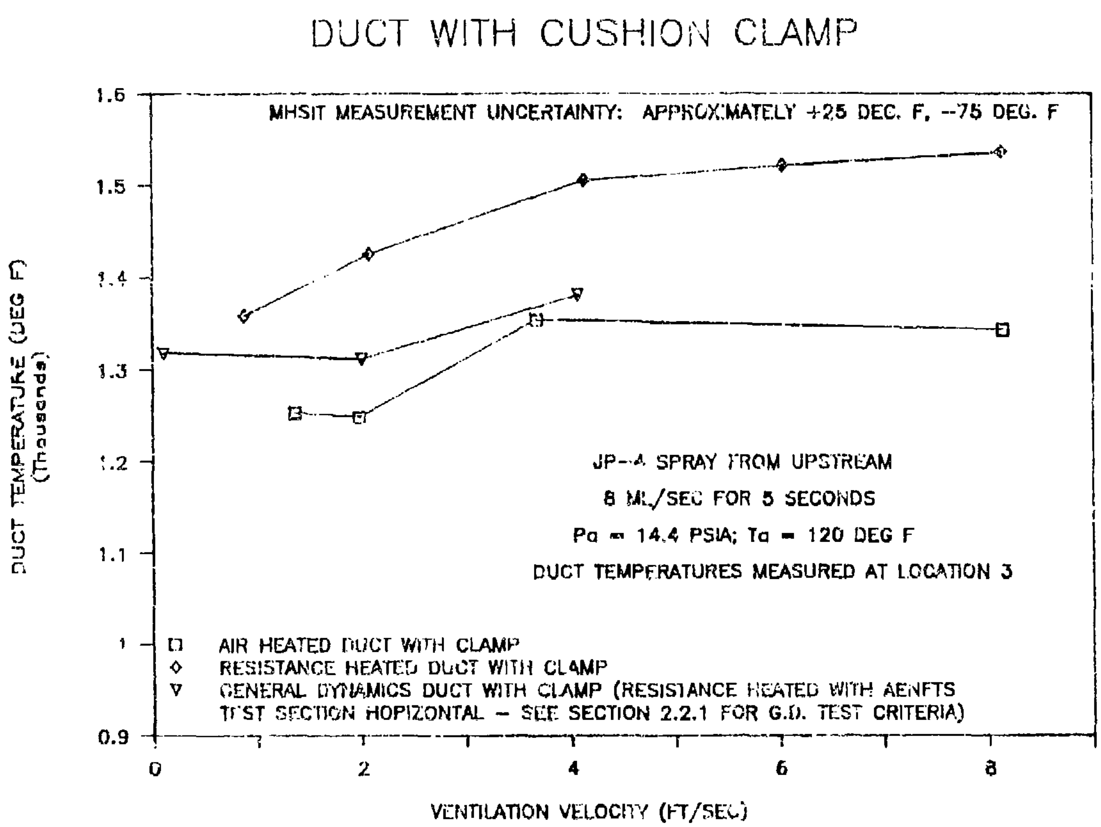
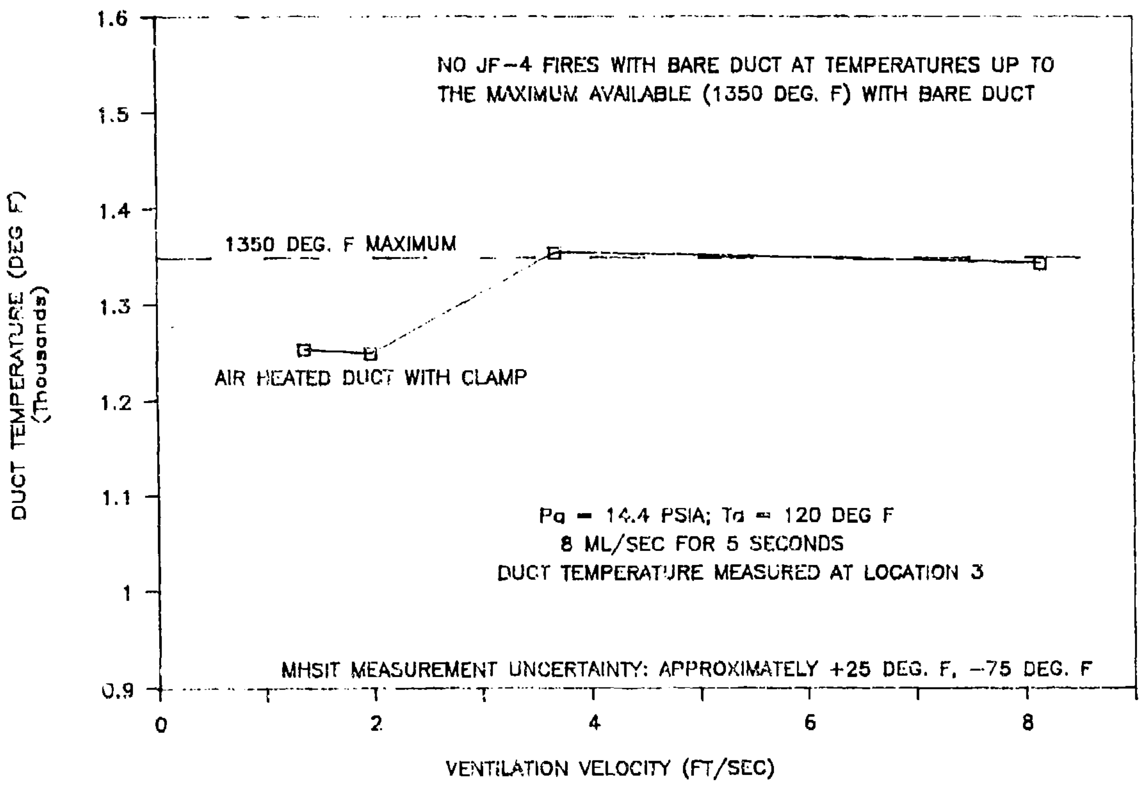


Figure 28. Effect of V_a on Simple Duct MHSIT for JP-4

JP-4 SPRAYED FROM UPSTREAM



5606 SPRAYED FROM UPSTREAM

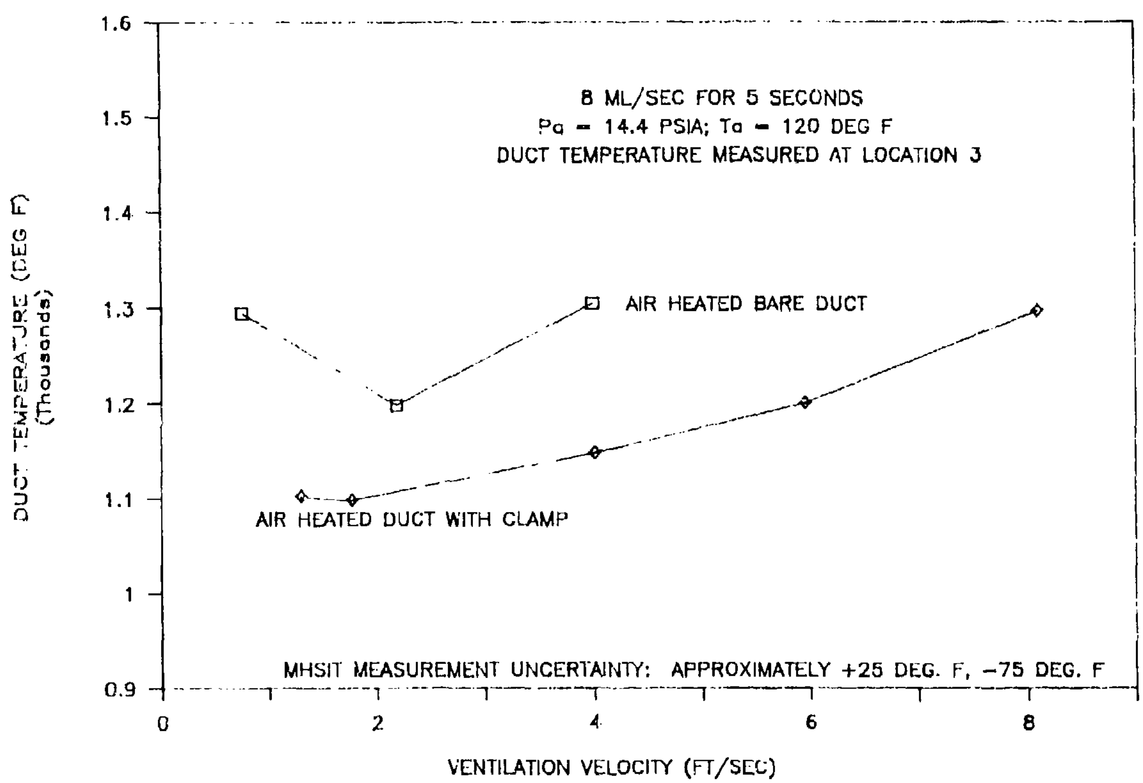
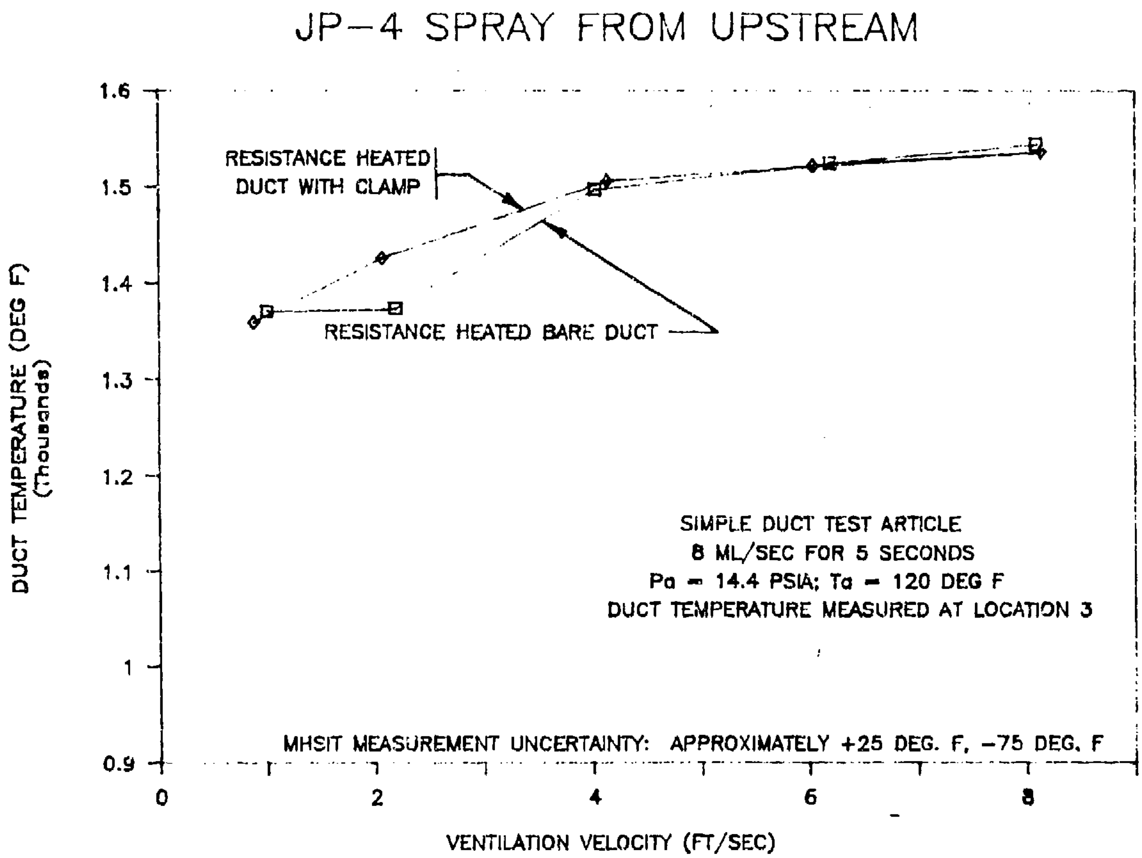


Figure 29. Effect of V_a on Air Heated Simple Duct MHSIT



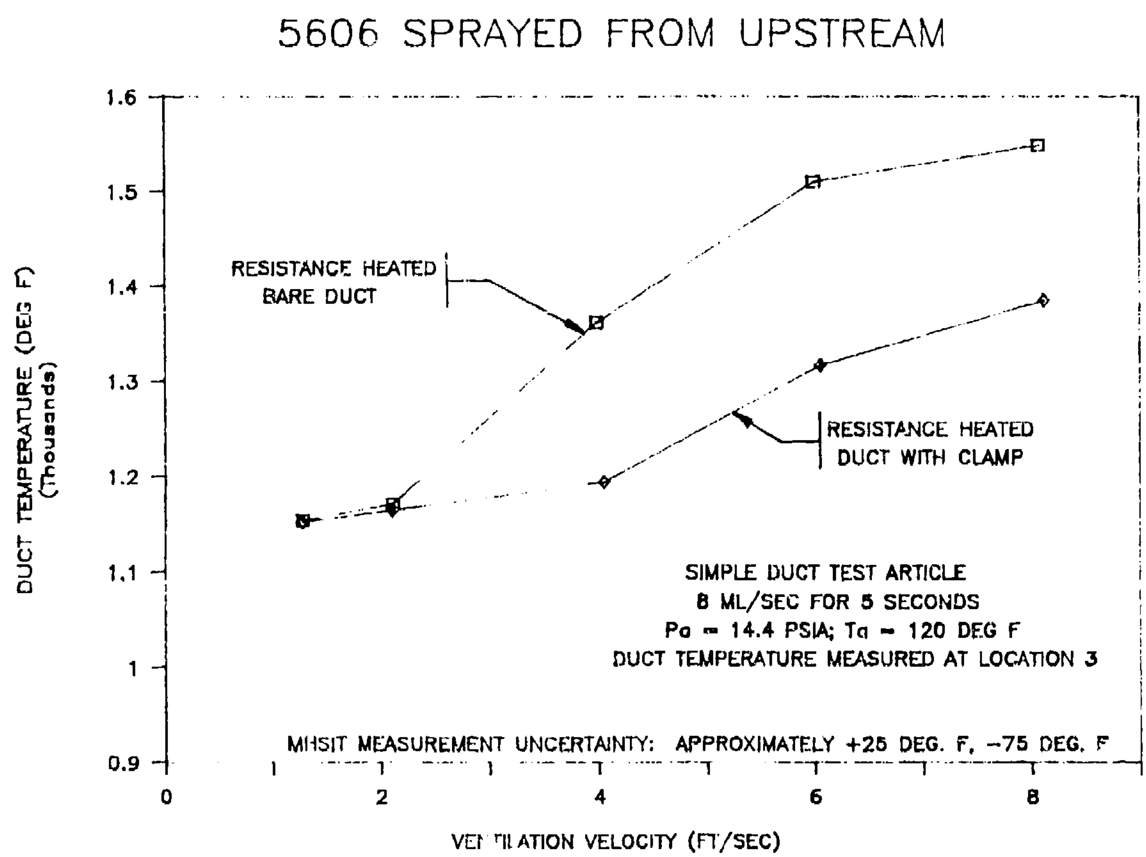


Figure 30. Effect of V_a on Resistance Heated Simple Duct MHSIT

Table 4. Summary of Results of Simple Duct Tests

ALL TEMPERATURES IN DEGREES F.

Pa = 14.4 PSIA (APPROXIMATE)
Ta = 120 DEG. F (APPROXIMATE)
All Fluids Sprayed from Upstream
AENFTS Test Section Horizontal Except as Noted

TEST CONFIGURATION	T/C POSITION	APPROXIMATE VENTILATION AIRFLOW VELOCITY (FT/SEC) 0	1	2	4	6	8
5606 - SIMPLE DUCT							
AIR HEATED SIMPLE DUCT	3	NO TEST	1300	1200	1300	NO FIRE	NO FIRE
AIR HEATED SIMPLE DUCT, AENFTS TEST SECTION IN VERTICAL POSITION	3	NO TEST	NO FIRE	NO FIRE	NO FIRE	NO TEST	NO TEST
RESISTANCE HEATED SIMPLE DUCT	3	NO TEST	1150	1170	1360	1510	1550
GENERAL DYNAMICS (RES. HTD. BARE DUCT)	4	1110	1010	1210	1310	1420	1430
5606 - DUCT WITH CUSHION CLAMP							
AIR HEATED DUCT WITH CLAMP	3	NO TEST	1100	1100	1150	1200	1300
RESISTANCE HEATED DUCT WITH CLAMP	3	NO TEST	1150	1170	1190	1320	1380
GENERAL DYNAMICS (RES. HTD. DUCT W/CLAMP)	4	1140	1050	1020	1320	1420	NO TEST
JP-4 - SIMPLE DUCT							
AIR HEATED SIMPLE DUCT	3	NO TEST	NO FIRE	NO FIRE	NO FIRE	NO FIRE	NO FIRE
RESISTANCE HEATED SIMPLE DUCT	3	NO TEST	1370	1370	1500	1520	1540
GENERAL DYNAMICS (RES. HTD. BARE DUCT)	4	1340	NO TEST	1320	1330	1330	1340
JP-4 - DUCT WITH CUSHION CLAMP							
AIR HEATED DUCT WITH CLAMP	3	NO TEST	1250	1250	1350	NO TEST	1340
RESISTANCE HEATED DUCT WITH CLAMP	3	NO TEST	1360	1430	1510	1520	1540
GENERAL DYNAMICS (RES. HTD. DUCT W/CLAMP)	4	1320	NO TEST	1310	1380	NO TEST	NO TEST

T/C POSITION: LOCATION OF THERMOCOUPLE EMPLOYED TO MEASURE MHSIT - SEE FIGURE 17 FOR DETAILS
NO TEST: NO HOT SURFACE IGNITION TEST PERFORMED AT THESE CONDITIONS
NO FIRE: IGNITION DID NOT OCUR AT 1350 DEG. F MAXIMUM AVAILABLE DUCT TEMPERATURE; MHSIT ASSUMED TO BE GREATER THAN 1350 DEG. F

MEASUREMENT UNCERTAINTY: APPROXIMATELY +25 DET. F, -75 DEG. F located in the horizontal position (Fig. 16) so that it represented the lower third of an aircraft engine compartment.

The third group of tests addressed (3) the effect of duct orientation on the MHSIT. Here the AENFTS test section was rotated to the vertical position, representing one-third of the right side of an aircraft engine compartment. Only 5606 was used in this group of tests. The data acquired with this configuration was compared to the 5606 air-heated bare-duct data from previous tests.

The effect of ventilation air velocity on MHSIT for 5606, for the air-heated bare duct, air-heated duct with clamp, resistance heated bare duct and resistance heated duct with clamp is shown in Figures 27. Similar data for JP-4 is shown in Figure 28. General Dynamics MHSIT data (Ref. 4) for 5606 and JP-4 for their resistance heated bare duct and resistance heated duct with clamp are also included on these figures.

With the resistance heated duct, thermocouple 3 was chosen to report duct temperature in all cases because it was consistently the hottest location monitored. There was little temperature variation on the air-heated simple duct so thermocouple 3 was again selected. It was felt that the highest temperature on the duct was closest to the MHSIT because the sprayed fluid reached all parts of the hot duct completely and ignition was likely to occur at the hottest point. As noted in Section 2.2.1, a different criteria was employed to select the reference thermocouple for the General Dynamics test data. The thermocouple with the consistently lowest reading was employed. As also noted in Section 2.2.1, it could be anticipated that this difference in reference thermocouple selection criteria would result in the General Dynamics MHSIT's being lower than those measured in the current program (from 50^{o}F lower at 1 ft/sec to nearly 200^{o}F lower at 8 ft/sec).

A trend for MHSIT to increase with ventilation velocity is apparent with 5606 Spray From Upstream (Fig. 27) . The General Dynamics data exhibits a dip in MHSIT at around 1 to 2 ft/sec. The dip is less pronounced in the current data though there is a similar dip in the air-heated bare-duct data. The facility maximum for air-heated bleed-duct temperatures was about 1350°F and there were no fires with the air-heated bare-duct at 6 and 8 ft/sec, probably because the duct was not hot enough. Hot surface ignition fires did occur with the air-heated bare-duct at 1 , 2 and 4 ft/sec. This suggests that the MHSIT's might continue to increase with ventilation velocity for the air heated bare duct as well, though they would have occurred at temperatures too high to observe in this program.

The presence of the cushion clamp lowered the MHSIT for 5606 for the air-heated and the resistance-heated cases, from 100°F to 200°F. This was probably because the clamp held the fluid next to the duct longer, allowing the fluid more time to heat than with the bare duct where it was blown away before it could ignite. The General Dynamics data for 5606, however, indicates very little effect of the clamp on MHSIT, except at 2 ft/sec where the MHSIT decreased by 200°F when the clamp was present.

Differences between resistance-heating and air-heating the simple duct can also be noted in Figure 27. The air-heated duct generally produced ignition at lower temperatures than the resistance-heated duct. Both the air-heated bare-duct at 4 ft/sec and the air-heated duct with clamp at 1 to 8 ft/sec ignited the fluids at temperatures 50°F to 100°F lower than the resistance-heated counterparts.

Differences in the heating rates of the resistance-heated and air-heated simple duct test articles is illustrated in the temperature history of the duct thermocouples directly impacted by the spray (position 4), as shown in Figure 31. These data were obtained during similar tests with 5606 sprayed onto the duct with cushion clamp at a ventilation air velocity of 6 ft/sec. The initial duct temperature was set at 1300°F and ignition was observed about 6 seconds after the 5606 spray was initiated. Little change in the heating rate at position 4 is seen following ignition, probably indicating that the fluid is burning elsewhere on the duct. Subsequent tests were run at 1250°F and 1200°F before the MHSIT for this condition was established to be 1200°F. As was shown in Figure 24, the thermocouple at location 3 (at the side of the duct), which was used as

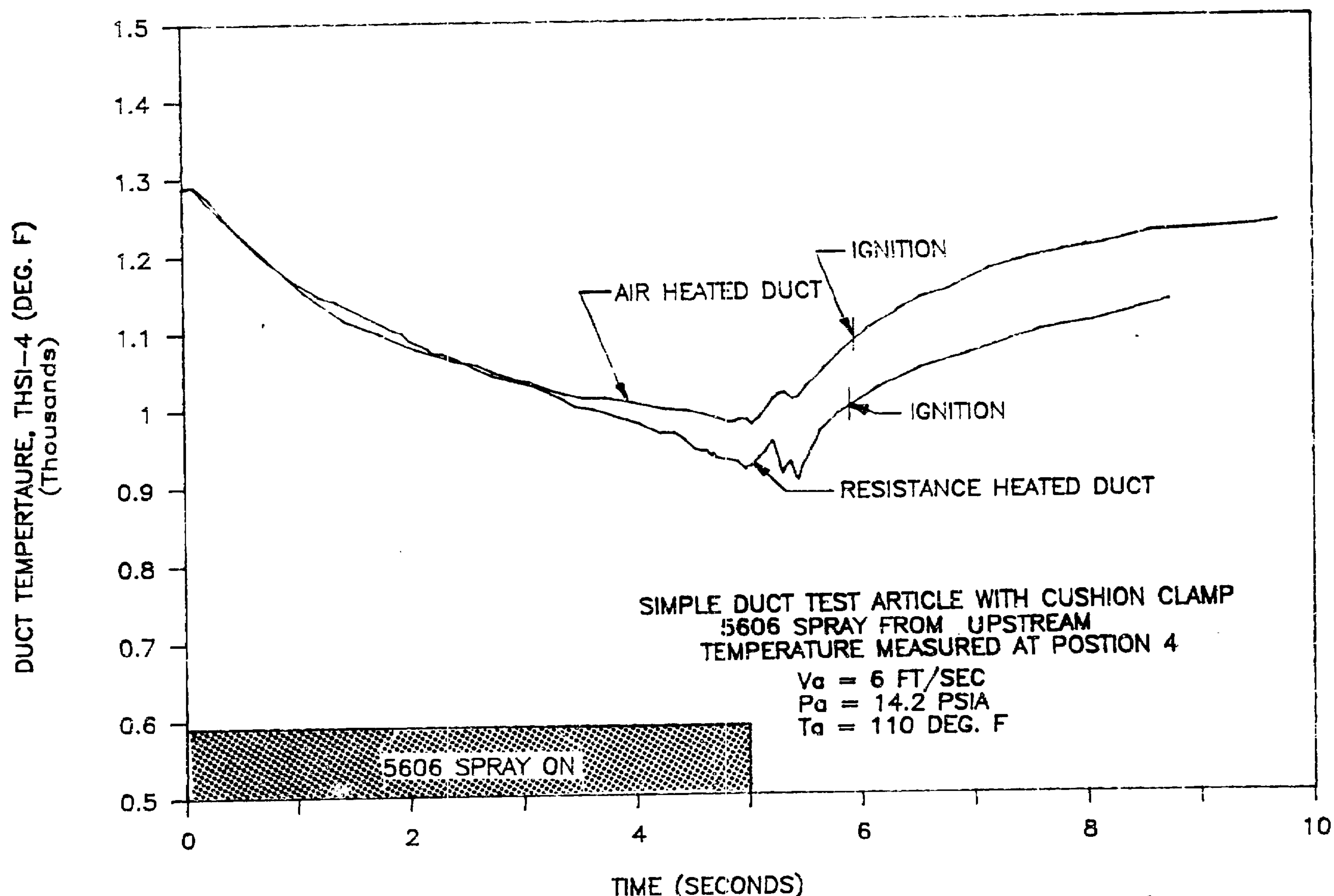


Figure 31. Variation in Duct Temperature with Time During Air-Heated and Resistance Heated Simple Duct Tests

the reference temperature to define the MHSIT's, did not experience the ubstantial cooling and reheating noted at position 4.

Figure 31 shows that the air-heated duct had a higher heating rate than the resistance-heated duct which led to a smaller temperature drop at position 4 when the relatively cold fluid was sprayed onto the duct and also to a faster temperature recovery. Because it was generally based on a manual record of a visual observation, accuracy of the ignition delay measurement, estimated at ± 0.25 seconds, is probably inadequate to conclude anything from the ignitions times noted on the plot.

There was a recurring problem with leakage of bleed-air during the simple duct testing. Leaks in the bleed duct assembly were discovered when the test section viewing window was opened on three different occasions. These leaks occurred only at the welds on the duct about 12 inches downstream from the target area (the location is noted in Detail 2 of Figure 16). With the window removed and 1 lb/sec of ambient temperature bleed air flowing through the duct, the leakage could be manually felt no further than 3 inches from the leak. On each occasion that leakage was discovered, repairs were made before testing resumed. Because it is impossible to identify when the leakage recurred, however, this must be interpreted as a minor source of uncertainty in the quality of all of the simple duct data. (This problem was permanently corrected prior to the high realism phase of hot surface ignition testing.)

Some of the same trends seen with 5606 can be seen with JP-4 (Fig. 28). No data for the air-heated bare-duct is shown because there were no ignitions of JP-4 spray, up to the facility maximum duct temperature of 1350°F. Hence, JP-4 spray on an air-heated bare-duct has a MHSIT greater than 1350°F at ventilation velocities less than 8 ft/sec.

The cushion clamp had less effect on JP-4's MHSIT than on 5606's MHSIT. As with the General Dynamics tests, the resistance heated duct data shows little or no effect of the clamp on MHSIT. Above 4 ft/sec the current resistance-heated duct MHSIT continues to increase as the velocity increases. The General Dynamics MHSIT remained constant. The lowest

MHSIT was again found with the air-heated duct with clamp. No ignition was observed at velocities greater than 4 ft/sec with the air heated duct, again probably because the MHSIT was above the 1350°F maximum temperature available.

The MHSIT's determined when JP-4 and 5606 were sprayed onto the air-heated duct are compared on Figure 29. JP-4 ignited at higher temperatures than 5606, probably because of its higher volatility. This allowed it to vaporize faster and hence required less time in contact with the hot duct for ignition to occur. This general trend in MHSIT was demonstrated throughout the test program for other fluids as well as with JP-4 and 5606; the more volatile the fluid, the higher its MHSIT.

Figure 30 shows a similar comparison for the resistance-heated simple-duct. While the MHSIT's are generally higher for JP-4 than 5606, ventilation velocity seemed to have a greater effect on the MHSIT of 5606 than JP-4. The MHSIT for JP-4 increased 200°F from 1 to 8 ft/sec while the MHSIT for 5606 increase about 250°F for the duct with clamp and 400°F for the bare duct. This large rise in the 5606 bare duct MHSIT actually causes the ignition temperatures for 5606 bare duct to be equal to the JP-4 MHSIT at 6 and 8 ft/sec. The MHSIT for JP-4 appears to depend less on the ventilation velocity than 5606.

The effect of test section and duct orientation on MHSIT was also examined in the simple duct test. 5606 was sprayed on the vertical air-heated bare-duct and the MHSIT's were to be compared to the horizontal duct data that was taken earlier in the test program. While fires were ignited at 1, 2 and 4 ft/sec in the horizontal test, no ignitions at all were recorded in the vertical test.

As will be discussed in detail in Section 4.2, it was found during the high-realism tests that fluid stream ignition temperatures for a vertical length of bare duct were much higher than the MHSIT for a fluid stream on a horizontal length of bleed duct. Natural convection patterns were observed around the simple duct caused by smoke rising and swirling from the fluid being heated on the duct. These patterns were observed to be much more active when the duct was in the vertical position than when it was installed in the horizontal position suggesting that there were greater variations in local velocity for the same ventilation airflow rate. This higher effective ventilation velocity may have been responsible for raising the vertical duct MHSIT for 5606 above the available facility maximum temperature.

4.2 High Realism Tests

The High Realism Tests were intended to simulate hot surface ignition scenarios in an F-16 engine compartment. To accomplish this the simple duct test article was removed and the F-16 nacelle simulator, containing an actual F-16 bleed air duct and other engine components was installed in the AENFTS test section. As illustrated in Table 5, the effect of many engine compartment variables on the MHSIT of the five test fluids (5606, 83282, 7808, JP-4 and JP-8) were studied in the high realism tests.

The high realism tests were classified into two general groups: (1) conditions of fluid injection and (2) the effects of ventilation air conditions on MHSIT. The first dealt with the effect of injection location, flowrate and duration on MHSIT. The second group of tests concerned the effect of ventilation air pressure, temperature and velocity on the MHSIT of each fluid at stream and spray locations selected from those tried during the first group of tests.

Because the objective of this test series was realistic stimulation of the F-16 engine compartment, the AENFTS test section was installed in its vertical position. The results obtained with the simple duct test article, however, had indicated that horizontal placement of the AENFTS test section resulted in the lowest MHSIT's than vertical placement. Hence, although the bleed air duct of the realistic test article had both vertical and horizontal sections, lower MHSIT values may have been observed had the AENFTS test section been installed in the horizontal position for these tests.

TABLE 5. High Realism Test Matrix

	CONDITIONS OF VENTILATION AIR			FLUIDS				
	Pressure (psia)	Temperature (deg. F)	Velocity (ft/sec)	JP-4	JP-8	5606	83282	7808
1.0 CONDITIONS OF FLUID INJECTION								
1.1 EFFECT OF INJECTION LOCATION ON MHSIT								
Spray from Upstream	14.4	120	1	X	X	X	X	X
8ml/sec for 5 sec								
Spray from Downstrm	14.4	120	1	X	X	X	X	X
8ml/sec for 5 sec								
Stream loc 1 - 6	14.4	120	1	X	X	X	X	X
2ml/sec for 10 sec								
1.2 EFFECT OF INJECTION FLOWRATE/DURATION ON MHSIT								
Spray from upstream								
flowrate	14.4	120	0 - 8			X		
4,8,12 ml/s for 5sec								
Stream at location 3								
flowrate	14.4	120	1			X		
1,2,3 ml/s for 10sec								
duration	14.4	120	1			X		
10sec,40sec @ 2ml/s								
2.0 EFFECTS OF VENTILATION AIR CONDITIONS ON MHSIT								
2.1 SPRAY (8ml/sec for 5 sec)								
From Downstream								
Air Pressure								
Ram simulation	14.4, 20	120	11	X	X	X	X	X
Altitude simulation	5,10,14.4	120	2	X	X	X	X	X
Air Temperature	14.4	120,300,600	2	X	X	X	X	X
Air Velocity	14.4	120	0 - 8				X	
Baffle	14.4	120	11	X	X	X	X	X
No bleed air flow	14.4	480 - 600	2				X	
From Upstream								
Air Velocity	14.4	120	0 - 8			X		
2.2 STREAM (2ml/sec for 10 sec)								
Location 3								
Air Pressure								
Ram simulation	14.4, 20	120	11			X	X	X
Altitude simulation	5,10,14.4	120	2			X	X	X
Air Temperature	14.4	120,300,600	2			X	X	X
Air Velocity	14.4	120	0 - 8			X	X	X
Baffle	14.4	120	11			X	X	X
Location 5								
Air Pressure								
Ram simulation	14.4, 20	120	11	X	X			
Altitude simulation	5,10,14.4	120	2	X	X			
Air Temperature	14.4	120,300,600	2	X	X			
Air Velocity	14.4	120	0 - 8	X	X			
Baffle	14.4	120	11	X	X			

NOTE: All tests with vertical nacelle and air heated duct

4.2.1 Conditions of Fluid Injection

There were two fluid spray locations (from upstream of the bleed duct and from downstream of the bleed duct) and six fluid stream locations where the five fluids were injected. The fluid injection locations are identified in Figure 21. The initial tests were conducted at a ventilation airflow velocity of 1 ft/sec, temperature of 120°F and pressure of 14.4 psia. The purpose of these tests was to determine the injection location at which the fluid ignited at the lowest temperature. The fluids were then injected at these locations during subsequent hot surface ignition testing.

The results of these tests are summarized in Figure 32. The MHSIT for each fluid is plotted versus injection location. Usually, 5606 and 83282 had the lowest MHSIT's, especially at stream location 3 (DL-3). Stream location 3 was at the top of a bend in the bleed-air duct, a horizontal bare duct surface similar to that used in the bare-duct simple duct tests. The thermocouple at position 3 (THSI-4) was the closest to stream location 3 and was used to report the duct temperature at this location. 7808 also had a minimum MHSIT at stream location 3. Hence, later testing in this program for 5606, 83282 and 7808 occurred at stream location 3.

83282 spray from downstream also ignited at a lower temperature than the other fluids. Hence, further testing was performed using 83282 spray from downstream. This spray location was also used for the spray comparison for all fluids in later tests. Thermocouple location 3 generally read the highest temperature on the bleed duct and since the spray contacted many locations on the duct, it was felt that the hottest temperature would most closely represent the MHSIT. For this reason, thermocouple location 3 was used to report duct temperature on the high realism bleed duct for all spray tests.

Stream location 5 was used as the fluid stream testing location for JP-4 and JP-8. While it was not the minimum igniting location for these two fluids, location 1 having provided lower ignition temperatures for JP-4, it was felt that the thick bleed duct fitting existing there (which was

HIGH REALISM TEST ARTICLE

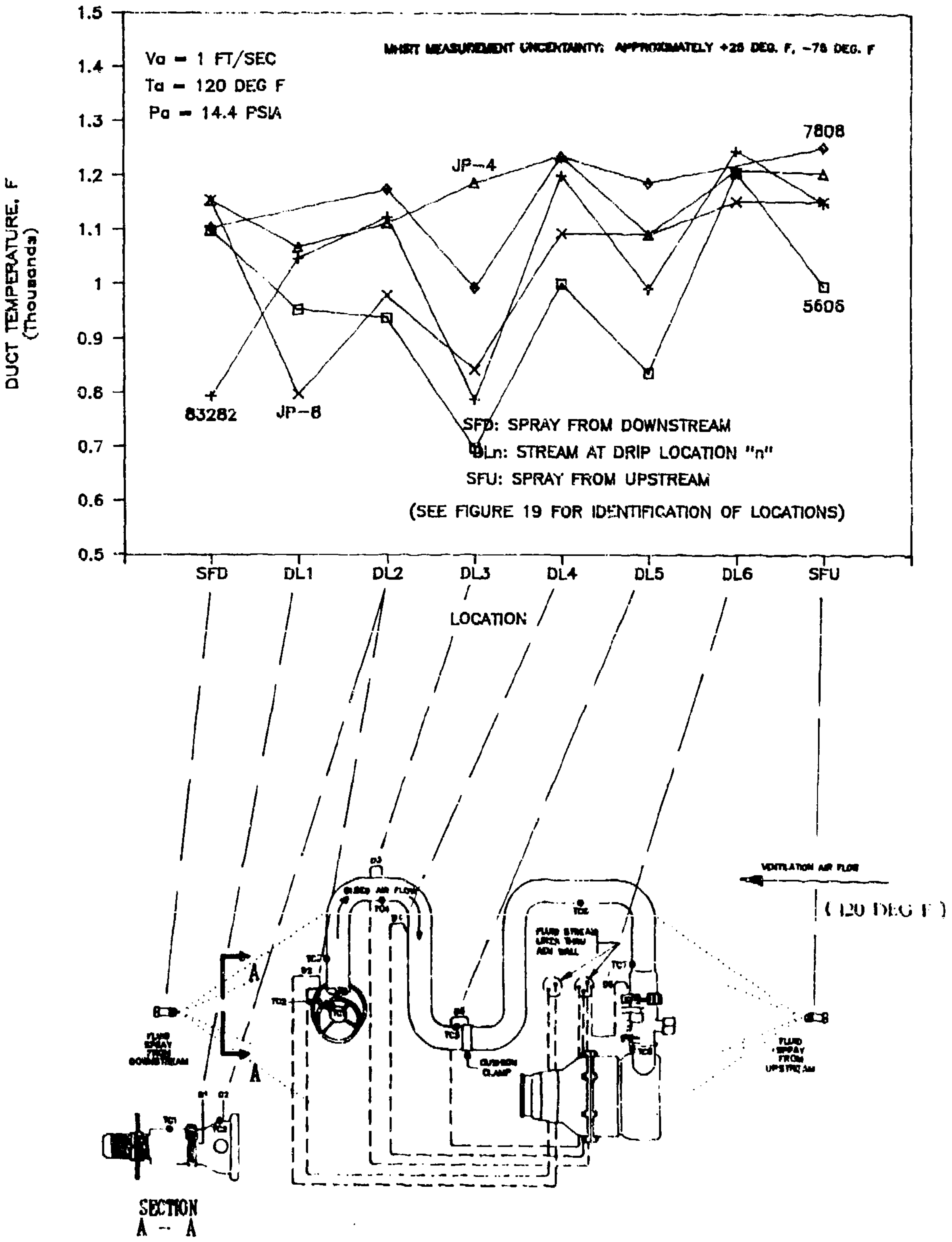


Figure 32. Effect of Spray and Stream Location on MHSIT with High-Realism Test Article

not a part of the F-16 nacelle) caused this to be an unrealistic location. Stream location 5 was at the bottom of a duct bend where a cushion loop clamp has been placed. This was similar to the horizontal duct with clamp in the simple duct tests. Thermocouple 5 (THSI-5), the closest thermocouple to stream location 5, was used to report the duct temperature at this location.

Figure 32 indicates that 5606 had the lowest MHSIT of the five fluids at most locations. In order of increasing MHSIT, 83282, JP-8, 7808 and JP-4 followed. In all these tests except for spray from downstream, 83282 ignited at higher MHSIT's than 5606. Generally the fluid stream ignited at lower temperatures than the fluid spray, an exception being 83282 spray from downstream which ignited at the same MHSIT as 83282 stream at location 3.

The test to determine the effect of injection flowrate and duration on MHSIT was performed only with 5606. 5606 was sprayed from upstream at 4, 8, 12 ml/sec for 5 seconds at various ventilation velocities ranging from 0 to 8 ft/sec. Figure 33 shows 5606's MHSIT for the three spray flowrates as the ventilation airflow rate changes and shows that the spray flowrate has little effect on the MHSIT.

The effect of stream flowrate on MHSIT was also examined. 5606 was injected on location 3 at 1, 2, 3 ml/sec for 10 seconds at a ventilation velocity of 1 ft/sec. Table 6 shows the MHSIT for those stream flowrates. Also included in Table 6 is MHSIT data for 2 ml/sec for 40 seconds. Neither the stream flowrates evaluated nor the injection duration seemed to effect the MHSIT significantly.

The flowrate and the injection duration seem only to effect air/fluid mixing characteristics at these fairly low flowrates. They appear to have had little effect on the MHSIT, probably because the duct temperature response did not differ as the flowrates were changed these small amounts. If the flowrates were increased enough to quench the entire duct significantly, the MHSIT probably would have been higher.

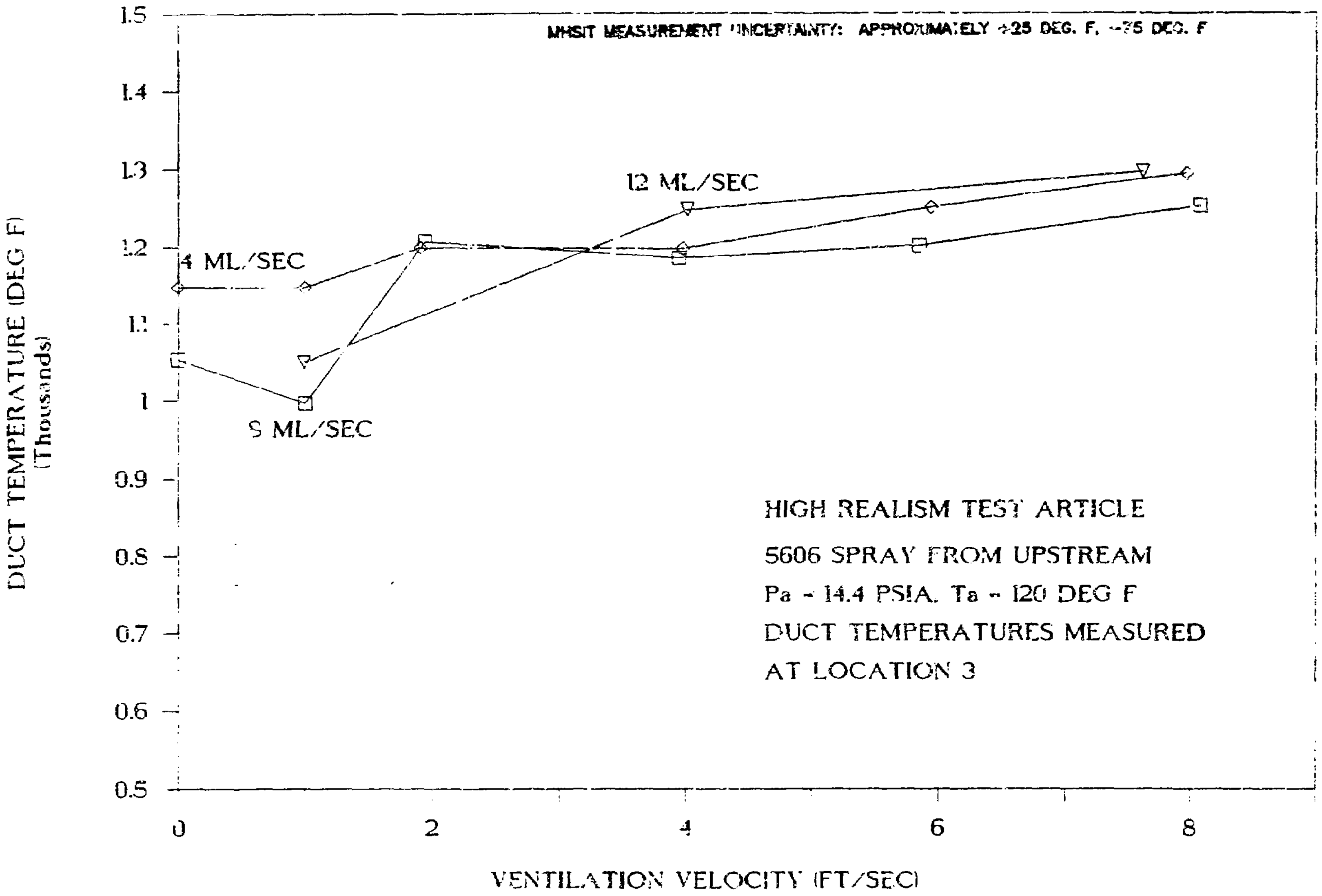


Figure 33. Effect of 5606 Spray Flowrate on MHSIT

Table 6. Effect of Stream Flowrate and Injection Time on MHSIT

STREAM INJECTION OF 5606 AT LOCATION 3 Va = 1 FT/SEC, Ta = 120 deg. F, Pa = 14.4 PSIA		
FLOWRATE (ML/SEC)	DURATION (SECONDS)	MHSIT (DEG. F)
1	10	786
2	10	738 (1/28/88 TEST)
2	10	782 (2/1/88 TEST)
2	40	739
3	10	786

4.2.2 The Effect of Ventilation Air Conditions on MHSIT

The first part of this group of tests dealt with the MHSIT's determined for the 5 fluids with spray injection when the ventilation air pressure, temperature and velocity were varied. In addition, the effect of a baffle, installed to change the airflow dynamics in the test article, was investigated. A test where no heat was supplied to the bleed duct and the effect of elevated ventilation airflow temperature on the MHSIT of 83282 was also conducted. A similar group of tests was run next using a fluid stream at location 3 (5606, 83282, 7808) or location 5 (JP-4, JP-8) instead of a spray (See Figure 21 for location identification). A summary of the effects of ventilation air pressure, temperature and velocity on MHSIT is provided in Tables 7, 8 and 9.

4.2.2.1 Spray

The first ventilation air variable tested during the spray test was ventilation air pressure (Fig. 34). All fluids were sprayed at 8 ml/sec for 5 seconds. Design limitation of the AENFTS prevented employment of the same ventilation airflow velocities for the high pressure (ram simulation) and low pressure (altitude simulation) tests, complicating direct comparison between high and low pressure MHSIT data. High pressure test conditions were obtained by closing the 24 inch valve downstream of the diffuser section and throttling the airflow exiting the test section with the 8 inch valve leading to the AENFTS ejector. There was sufficient leakage around these valves that it required a minimum airflow velocity of 11 ft/sec to reach 20 psia in the test section. The low pressure test conditions employed the AENFTS ejector system, again with the 24 inch valve closed and the 8 inch valve employed for downstream throttling. To reach 5 psia in the test section, a maximum airflow of 2 ft/sec could be handled by the ejector.

As the ventilation air pressure decreased, the MHSIT was expected to increase. Actually, none of the sprayed fluids were ignited up to the facility maximum bleed duct temperature (1350°F) at 5 or 10 psia. However, a trend in the MHSIT can be seen in the data taken at 14.4 and 20

Table 7. Summary of the Effect of Air Pressure on MHSIT

ALL TEMPERATURES IN DEGREES F.

FLUID INTRODUCTION	T/C POSITION	FLUID	ALTITUDE SIMULATION Va = 2 FT/SEC (APPROXIMATE) Ta = 120 DEG. F (APPROXIMATE)			RAM SIMULATION Va = 11 FT/SEC (APPROXIMATE) Ta = 120 DEG. F (APPROXIMATE)	
			APPROXIMATE AIR PRESSURE (PSIA)				
			5	10	14.4	14.4	20
STREAM INJECTION LOCATION							
3	4	5606	1320	1100	740	1140	1080
3	4	83282	1350	1150	840	1180	840
3	4	7808	NO FIRE	1340	990	1230	1140
5	5	JP-4	NO FIRE	1210	1200	1320	1240
5	5	JP-8	NO FIRE	NO FIRE	1150	1220	1240
SPRAY FROM DOWNSTREAM	3	5606	NO FIRE	NO FIRE	750	1300	1200
	3	83282	NO FIRE	NO FIRE	800	1220	820
	3	7808	NO FIRE	NO FIRE	1060	1270	1190
	3	JP-4	NO FIRE	NO FIRE	1160	1330	1240
	3	JP-8	NO FIRE	NO FIRE	1100	1290	1250
SPRAY FROM UPSTREAM	3	5606	NO TEST	NO TEST	1210	NO TEST	NO TEST

T/C POSITION: LOCATION OF THERMOCOUPLE EMPLOYED TO MEASURE MHSIT - SEE FIGURE 21 FOR DETAILS

NO FIRE: IGNITION DID NOT OCCUR AT 1350 DEG. F MAXIMUM AVAILABLE DUCT TEMPERATURE; MSHIT ASSUMED TO BE GREATER THAN 1350 DEG. F

NO TEST: NO HOT SURFACE IGNITION TEST PERFORMED AT THESE CONDITIONS

MHSIT MEASUREMENT UNCERTAINTY: APPROXIMATELY +25 DEG. F, -75 DEG. F

Table 8. Summary of the Effect of Air Temperature on MHSIT

Pa = 14.4 PSIA (APPROXIMATELY), Va = 2 FT/SEC (APPROXIMATELY)
ALL TEMPERATURES IN DEGREES F.

STREAM INJECTION LOCATION	T/C POSITION	FLUID	APPROXIMATE VENTILATION AIRFLOW TEMPERATURE (DEG. F) 120	300	600
3	4	5606	740	640	600
3	4	83282	840	750	600
3	4	7808	990	1040	850
5	5	JP-4	1180	1210	1180
5	5	JP-8	1130	940	1040
SPRAY FROM DOWNSTREAM	3	5606	750	700	600
	3	83282	800	650	*
	3	7808	1060	1060	950
	3	JP-4	1160	1050	750
	3	JP-8	1100	950	600

* 83282 WOULD IGNITE WITH AIR TEMPERATURE AT 600 DEG. F EVEN WITHOUT DUCT HEATING; SEE TEXT FOR EXPLANATION

T/C POSITION: LOCATION OF THERMOCOUPLE EMPLOYED TO MEASURE MHSIT - SEE FIG 21 FOR DETAILS

MHSIT MEASUREMENT UNCERTAINTY: APPROXIMATELY +25 DEG. F, -75 DEG. F

Table 9. Summary of the Effect of Air Velocity on MHSIT

Pa = 14.4 PSIA (APPROXIMATE)
Ta = 120 DEG. F (APPROXIMATE)

ALL TEMPERATURES IN DEGREES F.

	T/C POSITION	FLUID	APPROXIMATE VENTILATION AIRFLOW VELOCITY (FT/SEC)							
			0	1	2	4	6	8	11	11
STREAM INJECTION LOCATION			WITHOUT BAFFLE							WITH BAFFLE
3	3	5606	NO TEST	700	740	840	990	1040	1140	700
3	3	83282	790	790	840	800	840	850	1180	730
3	3	7808	NO TEST	990	990	1090	1090	1130	1230	1120
5	5	JP-4	1250	1200	1200	1250	1260	1310	1320	1210
5	5	JP-8	1160	1150	1150	1200	1250	1260	1220	1160
SPRAY FROM DOWNSTREA	3	5606	NO TEST	1100	750	NO TEST	NO TEST	NO TEST	1300	1250
	3	83282	750	800	800	750	800	1010	1220	1170
	3	7808	NO TEST	1100	1060	NO TEST	NO TEST	NO TEST	1270	1210
	3	JP-4	NO TEST	1150	1160	NO TEST	NO TEST	NO TEST	1330	1270
	3	JP-8	NO TEST	1150	1100	NO TEST	NO TEST	NO TEST	1290	1250
SPRAY FROM UPSTREAM	3	5606	1050	1000	1210	1180	1200	1250	NO TEST	NO TEST

NO TEST: NO HOT SURFACE IGNITION TEST PERFORMED AT THESE CONDITIONS
T/C POSITION: LOCATION OF THERMOCOUPLE EMPLOYED TO MEASURE MHSIT - SEE FIGURE 21 FOR DETAILS

MHSIT MEASUREMENT UNCERTAINTY: APPROXIMATELY +25 DEG. F, -75 DEG. F

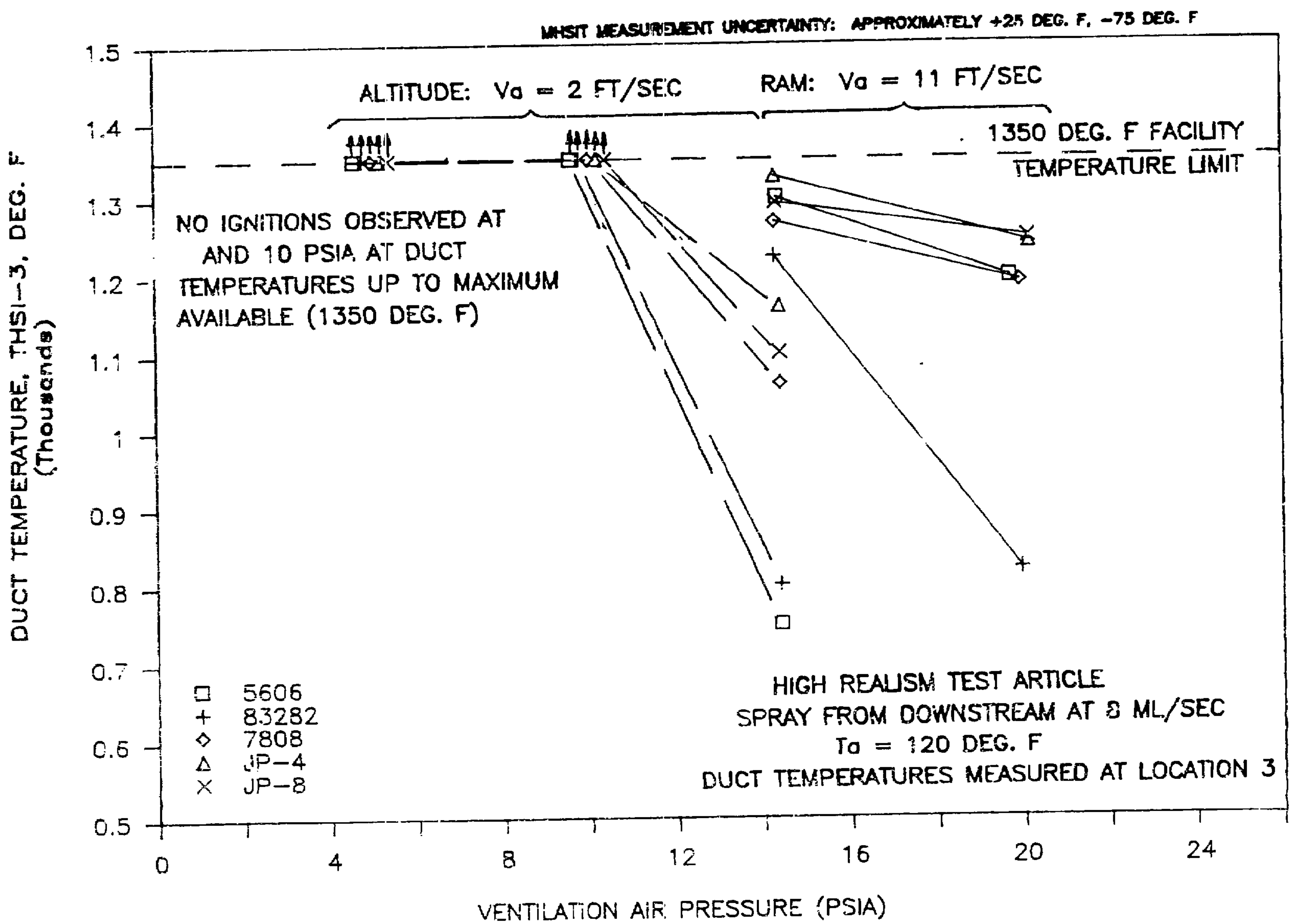


Figure 34. Effect of P_a on MHSIT with Fluid Spray

psia where the MHSIT's for all fluids decreased as the pressure increased. The MHSIT for 83282 spray from downstream decreased nearly 400°F as the ventilation air pressure was increased from 14.4 to 20 psia, in contrast to the other fluid's behavior where the differences were closer to 100°F.

The next variable that was examined in these tests was the effect of ventilation air temperature on MHSIT for all five fluids (Fig. 35). The MHSIT was determined for each of the fluids at ventilation air temperatures of 120°F, 300°F and 600°F, measured at location 3, just upstream of the heated bleed duct (Fig. 21). In all cases, the MHSIT's decreased as the ventilation air temperature was increased. This was probably largely due to the ventilation air-heating the fluid prior to its contacting the duct. This pre-heating of the air/combustible-fluid mixture reduced the heat transfer required from the duct to reach its ignition temperature. Hence ignition occurred with lower duct temperatures. The five fluids seemed to be affected differently: 7808 showed relatively little change (about 100°F) in MHSIT as ventilation air temperature was increased, as did 5606 (about 150°F). Conversely, JP-4 and JP-8 spray displayed a large decrease (400°F to 500°F) in MHSIT as the ventilation air temperature increased from 120°F to 600°F.

The MHSIT for 83282 at an air temperature of 300°F was 150°F lower than its MHSIT at an air temperature of 120°F. When the air temperature was increased to 600°F, however, the 83282 would consistently ignite even when the bleed air duct was cooler than the ventilation airflow. Since the AIT of 83282 is 670°F, it appeared that a situation had been encountered where a hot surface ignition temperature was lower than the fluid's AIT. Hence a second series of tests was performed that used hot ventilation air but no bleed air duct heating.

These tests were begun with the indicated ventilation air temperature at 600°F. Again, a 5 second spray of 83282 at 8 ml/sec ignited with no hot air being supplied to the bleed air duct. Next the air temperature was decreased incrementally until three fluid sprays tests had occurred without ignition at a ventilation air temperature of 480°F.

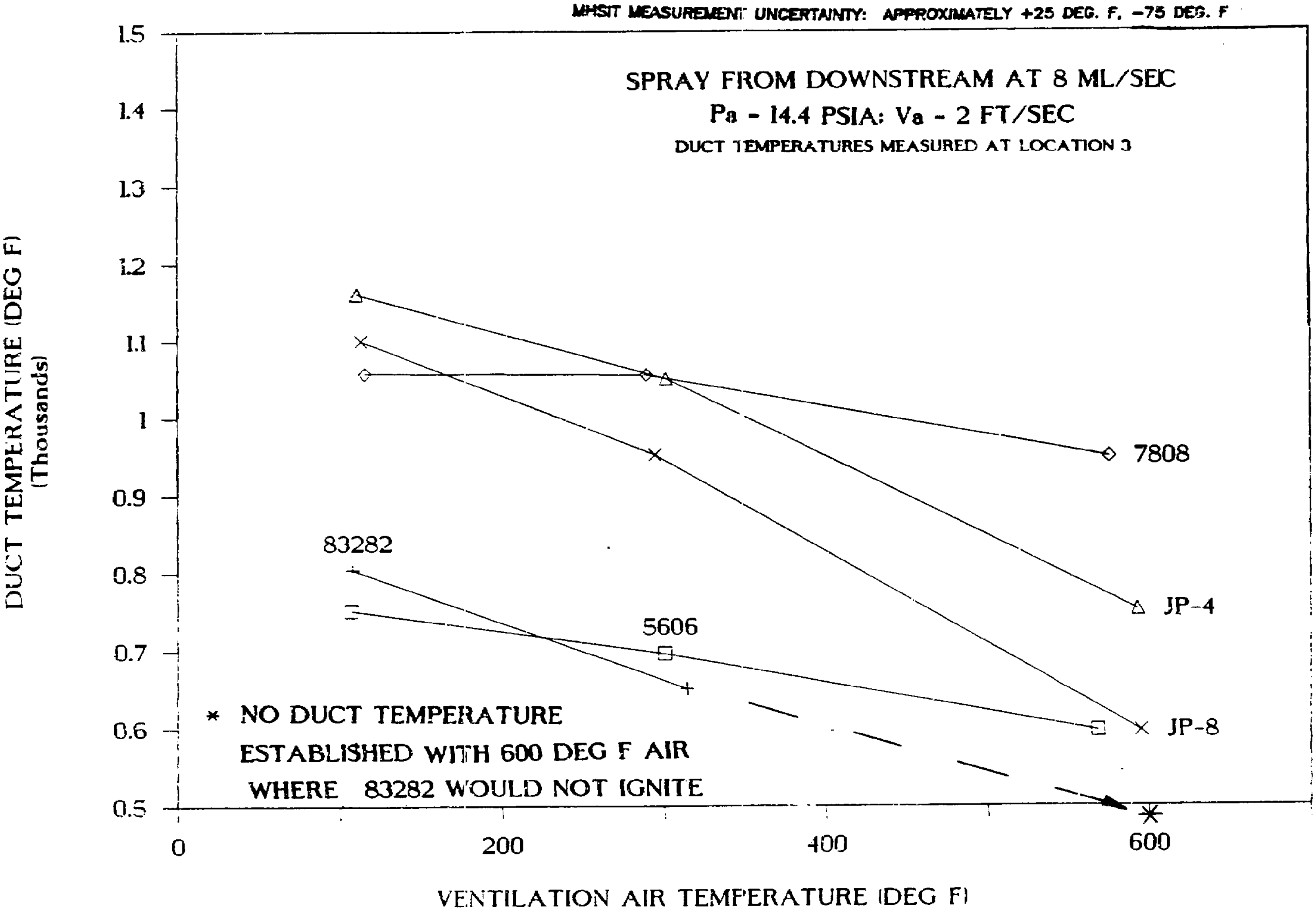


Figure 35. Effect of T_a on MHSIT with Fluid Sprcy

The duct temperature measured at location 3 provided erratic data during this test. Substituting data from the thermocouple at location 6, which normally provided similar duct temperature information to that at location 3, it appeared that the duct was normally only about 8°F to 10°F cooler than the airflow surrounding it (Fig. 36).

The duct temperature measured at the last test condition where an ignition had occurred, 510°F, was concluded to be 83282's MHSIT under these conditions. Before reaching specific conclusions about 83282's behavior under these conditions, however, some additional uncertainties must be considered:

1. Thermocouple error analysis, as documented in Appendix B, suggests that the duct thermocouples would generally indicate a temperature which was about 25°F lower than what actually existed on the duct. The last ignition occurred at an indicated duct temperature of 501°F, hence the actual duct temperature was probably about 526°F. Similar analysis of the air temperature thermocouples suggests that radiation error would be much larger and that the indicated temperature would be about 60°F lower than the actual air temperature with the specific conditions which existed during this test. Hence the air temperature had been about 570°F when the last ignition occurred.

2. Because it initially appeared that the 83282 did have a MHSIT below its AIT, material properties tests were conducted by the AFWAL/MLBT at the completion of the hot surface ignition testing on the actual fluids which had been used in these tests. The results of these tests, as shown in Table 10 indicate that (1) the fluids employed in these tests still met appropriate specifications after the tests had been completed and (2) the specific batch of 83282 used had an AIT of 700°F, per ASTM D 2155 and of 690°F, per ASTM E 659.

Hence The test results indicate that 83282 actually ignited in a situation where the air temperature was about 570°F and the duct temperature was about 530°F and that this specific batch of fluid had an AIT (per both ASTM D 2155 and E 659) more than 100°F higher than existed, either in the

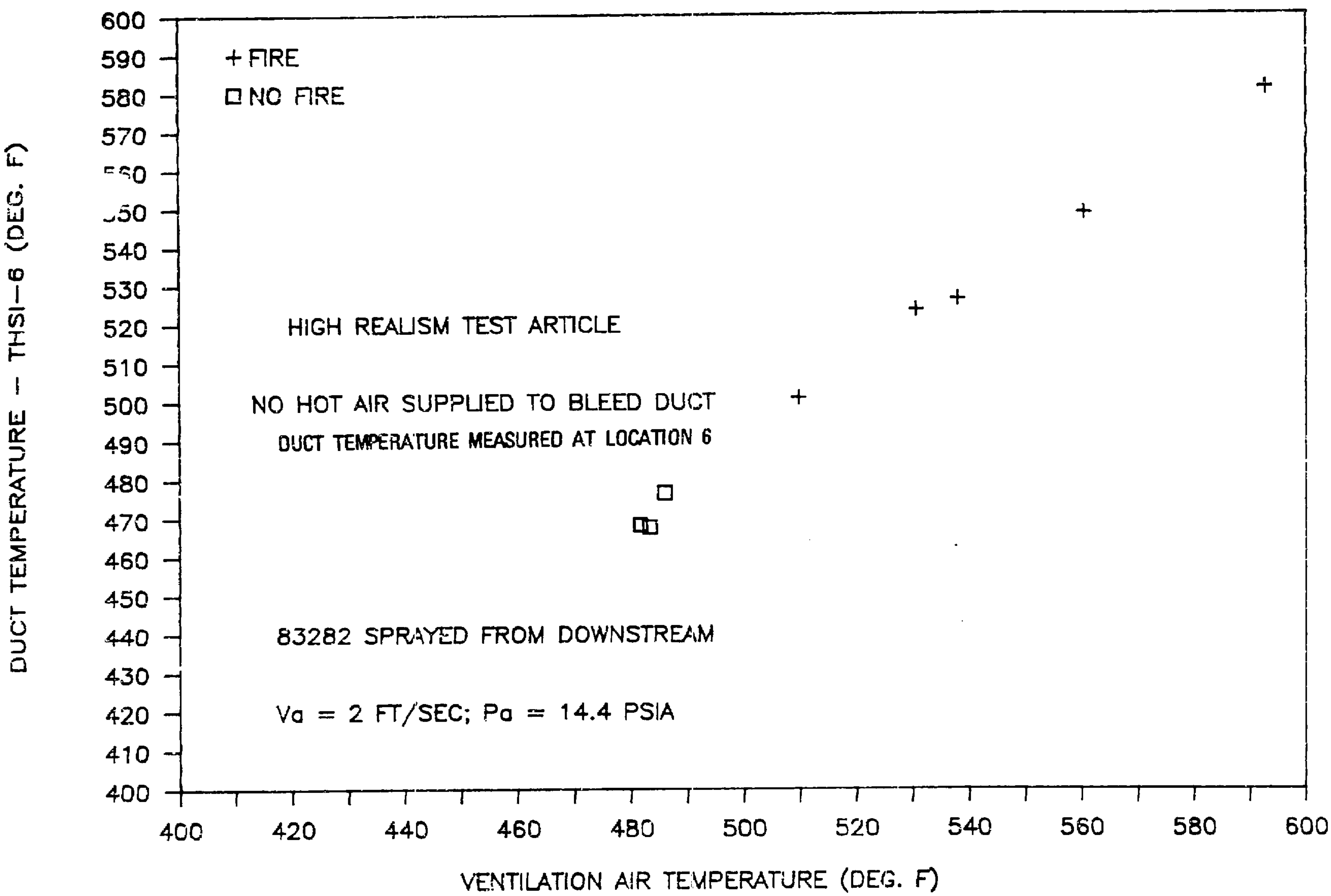


Figure 36. Effect of T_a on 83282 MHSIT with Fluid Spray

Table 10. Autoignition Temperature Test Results for Fluids Used in AENFTS Hot Surface Ignition Test Program

THE FOLLOWING DATA WERE ACQUIRED BY AFWAL/MLBT FOR SAMPLES OF THE SPECIFIC FLUIDS TESTED DURING THE AENFTS HOT SURFACE IGNITION TEST PROGRAM

	PER ASTM D2155			PER ASTM E659							FLASH POINT
	AUTOIGNITION TEMPERATURE (AIT)			AUTOIGNITION TEMPERATURE (AIT)			COOL-FLAME AUTOIGNITION TEMPERATURE (CFT)			REACTION THRESHOLD TEMPERATURE FOR PRE-FLAME REACTION (RIT)	PER ASTM D-92 AND ASTM D-93
FLUID	MINIMUM IGNITION TEMPERATURE (DEG. F)	IGNITION DELAY (SECONDS)	BAROMETRIC PRESSURE (TORR)	MINIMUM IGNITION TEMPERATURE (DEG. F)	IGNITION DELAY (SECONDS)	BAROMETRIC PRESSURE (TORR)	MINIMUM IGNITION TEMPERATURE (DEG. F)	IGNITION DELAY (SECONDS)	BAROMETRIC PRESSURE (TORR)	MINIMUM REACTION TEMPERATURE (DEG. F)	TEMPERATURE (DEG. F)
5606	440	240	747	425	342	748	N/O	N/O	N/O	415	192 (PER ASTM D-93)
83282	700	6	749	690	7	748	650	7	748	455	430 (PER ASTM D-92)
7808 1	725	4	747	713	4	749	700	22	748	510	460 (PER ASTM D-92)
7808 2	715	7	747	690	9	749	675	16	748	500	450 (PER ASTM D-92)
JP-4	490	87	745	440	250	748	N/O	N/O	N/O	441	NOT TESTED
JP-8	475	80	744	435	174	747	N/O	N/O	N/O	424	118 (PER ASTM D-93)

NOTES: N/O: WHILE THE TEST WAS RUN, NO "COOL FLAME" WAS IGNITION OBSERVED
TWO BATCHES OF MIL-L-7808 WERE USED INTERCHANGEABLY. THESE WERE IDENTIFIED AS:
1 SAMPLE NO. MLO-88-324 (J)
2 SAMPLE NO. MLO-88-325 (H)

air or on the duct during this test. The Reference 3 tests also found 83282 to have a hot surface ignition temperature below its AIT, 630°F (Figure 1) compared to an ASTM D 2155 AIT of 657°F.

Figure 37 shows the effect of ventilation velocity on the MHSIT for all five fluids when they were sprayed from downstream. This test was performed at a ventilation air pressure of 14.4 psia and a ventilation air temperature of 120°F. MHSIT data was acquired with 83282 at velocities of 0, 1, 2, 4, 6, 8 and 11 ft/sec while the MHSIT data for the other fluids were acquired only at 1, 2 and 11 ft/sec. 83282's MHSIT remained fairly constant at about 750°F to 800°F for ventilation velocities of 0 to 6 ft/sec and increased to 1000°F at 8 ft/sec and 1220°F at 11 ft/sec. The MHSIT's found for 5606 at 2 and 11 ft/sec are similar to those found for 83282. As was found during the simple duct testing (Fig 27), all five fluids show the same general trend of having a "dip" in their MHSIT at some intermediate velocity and having a substantially higher MHSIT at the highest velocities tested. Insufficient data was acquired to establish exactly where the "dip" occurs with 5606, 7808, JP-4 and JP-8. As with the simple duct testing, however, the 83282 MHSIT's are fairly constant from 0 to 4 ft/sec and begin to increase significantly beyond this point.

Caution is necessary if these test results are to be applied to an aircraft design problem. While the effect of increasing the velocity was, as anticipated, to generally increase the MHSIT's, these velocities were measured in a single location within the test article. As in an aircraft engine compartment, there were also regions of higher velocity and regions of stagnation. Unless the designer is confident of uniform airflow, the minimum MHSIT's found in these tests should be applied with the understanding that low local velocities may well exist in the vicinity of an aircraft bleed duct.

To examine the changes in the MHSIT's that could be caused by reduction in local ventilation velocities such as might be caused by blocking the ventilation airflow with an engine accessory, a baffle was installed in the test article (Fig. 12) to route the ventilation air away from the hot bleed duct where the fluids were sprayed. For these tests, the indicated

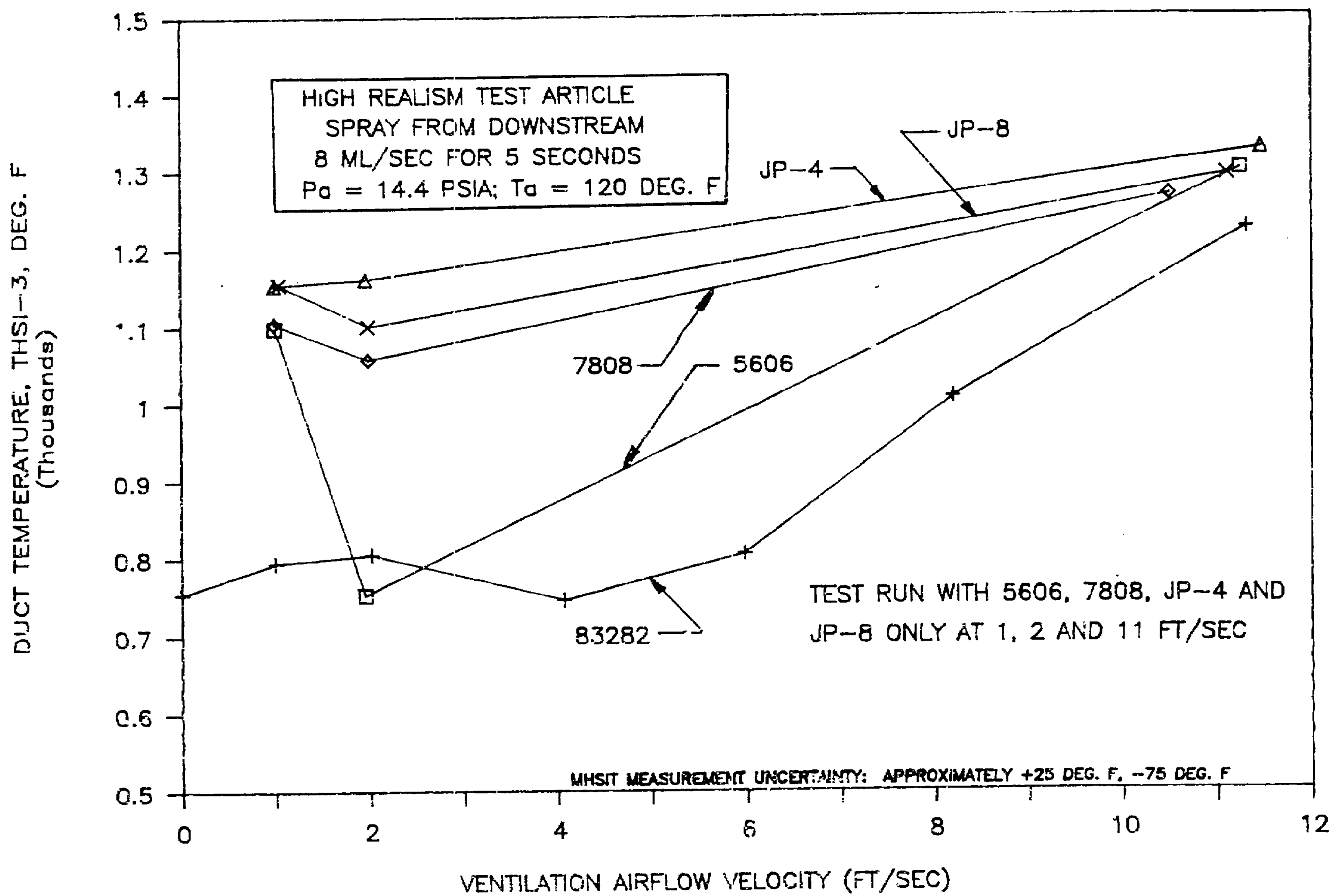


Figure 37. Effect of V_a on MHSIT with Fluid Spray

ventilation air velocity was 11 ft/sec. The actual velocity at the hot bleed duct was probably significantly lower but a pitot probe measurement was not made. The temperature was 120°F and the pressure was 14.4 psia. The MHSIT for each fluid, sprayed from downstream, both with and without the baffle, is shown in Figure 38. The baffle reduced the local ventilation velocity at the duct enough to lower the MHSIT's from 50°F to 200°F.

A test was also performed to observe the effect of ventilation velocity variation on the MHSIT of 5606 when sprayed from upstream. The MHSIT's that were measured are contrasted with the MHSIT's determined when 5606 was sprayed from downstream in Figure 39. While the MHSIT measured during the upstream spray test remained fairly constant from 2 to 8 ft/sec, the MHSIT at 8 ft/sec is about 200°F higher than the MHSIT at 0 ft/sec. The lowest MHSIT for 5606 (750°F) remained that measured at 2 ft/sec with spray from downstream.

4.2.2.2 Stream

Two stream locations were used for testing in this phase of the program: (1) Stream location 3, which resembled the horizontal bare duct in the simple duct tests, the location that produced ignitions at the lowest temperature for 5606, 83282 and 7808 in earlier testing. This was again used with 5606, 83282 and 7808. (2) Stream location 5, which resembled the horizontal duct with clamp in the simple duct tests, (along with Stream location 1, which was not considered to be representative of the duct installation in the aircraft) had produced ignition at the lowest temperature for JP-4 in earlier tests (Fig. 32). This location was used for JP-4 and JP-8 testing. At both of these locations, fluid streams were injected at 2 ml/sec for 10 seconds.

The effect of ventilation air pressure on MHSIT for all the fluids at these stream locations is shown in Figure 40. The hollow symbols are MHSIT data for 14.4, 10 and 5 psia at a velocity of 2 ft/sec. The solid symbols represent the MHSIT for the fluids at 14.4 and 20 psia ventilation

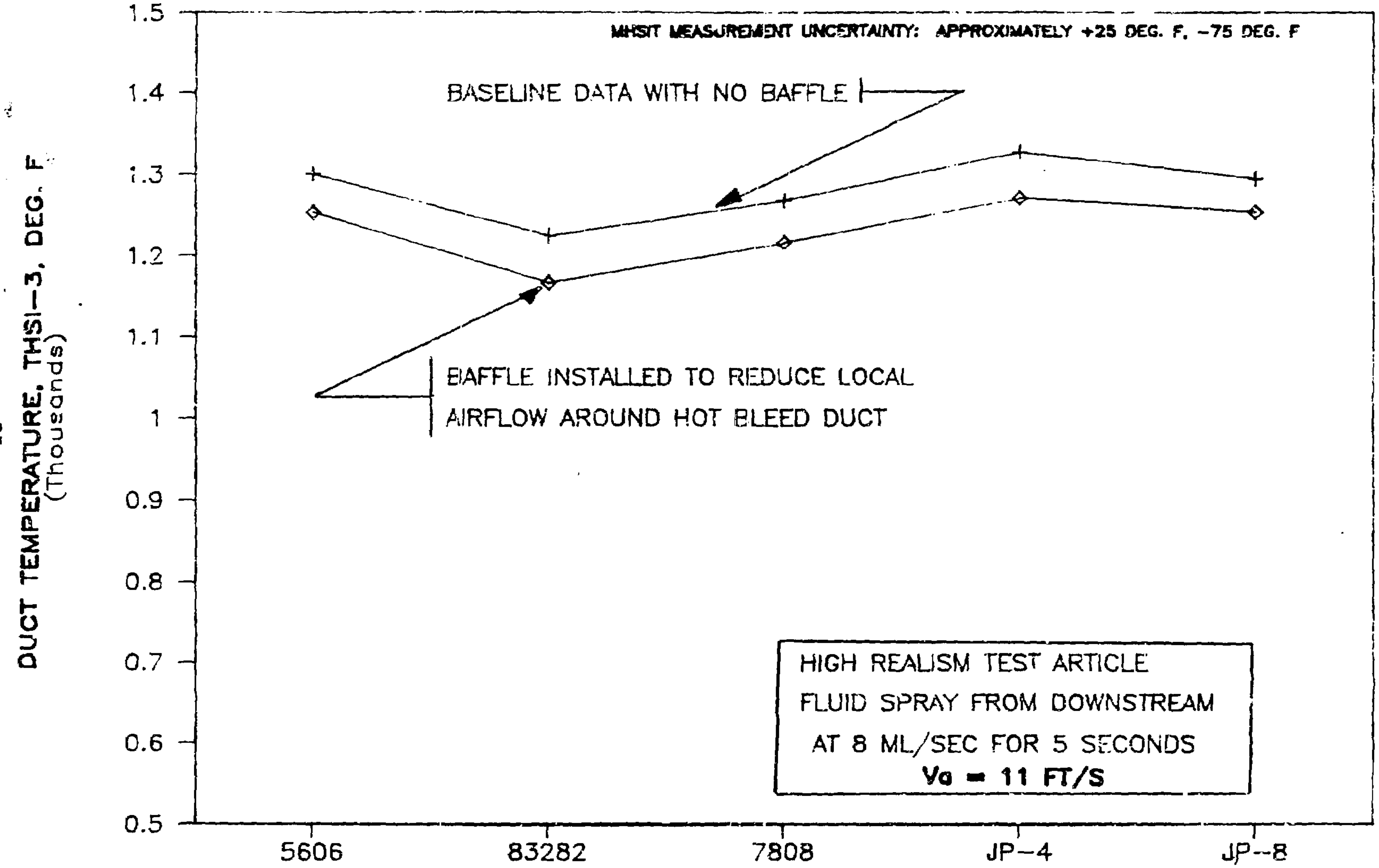


Figure 38. Effect of a Baffle on MHSIT with Fluid Spray

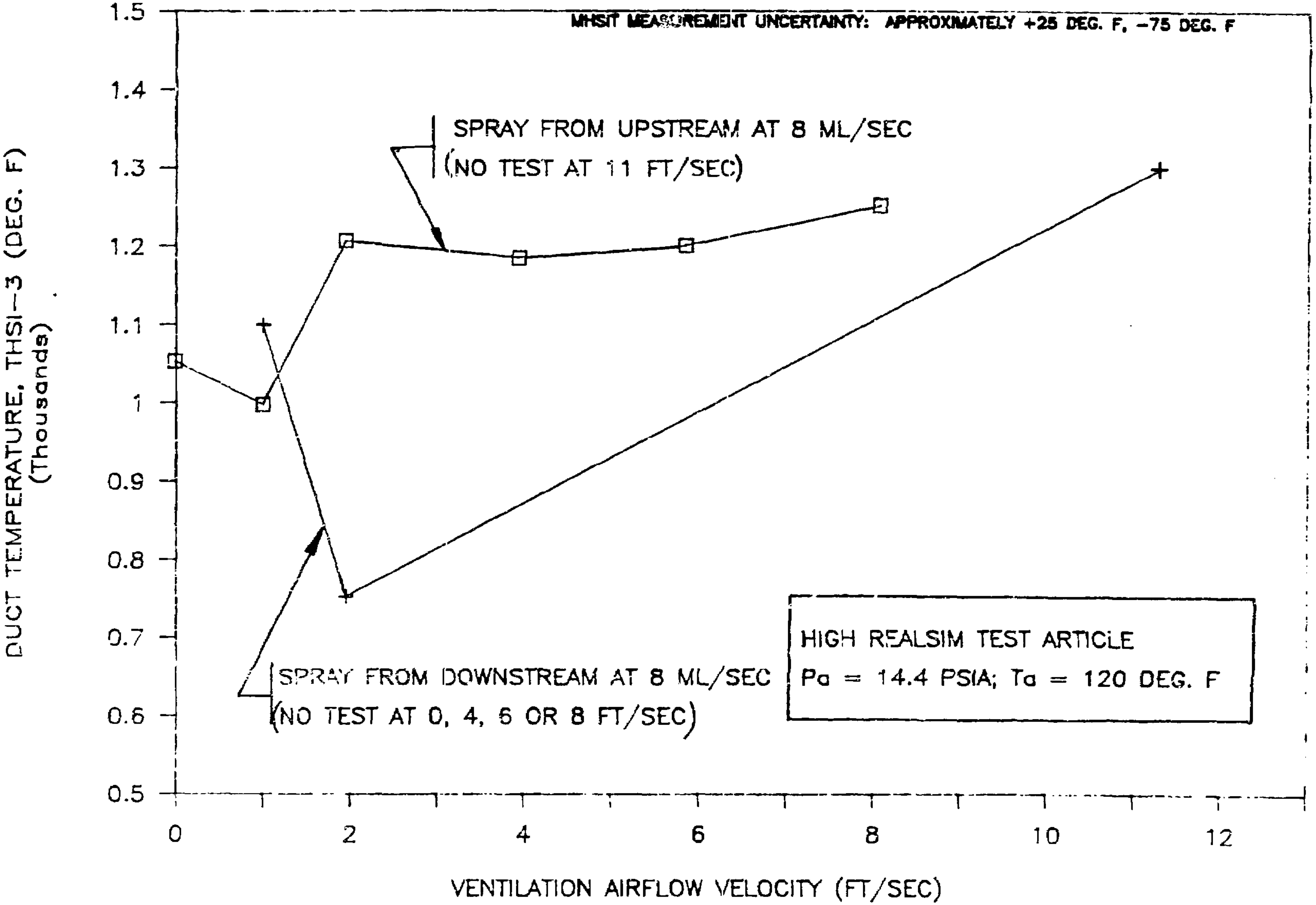
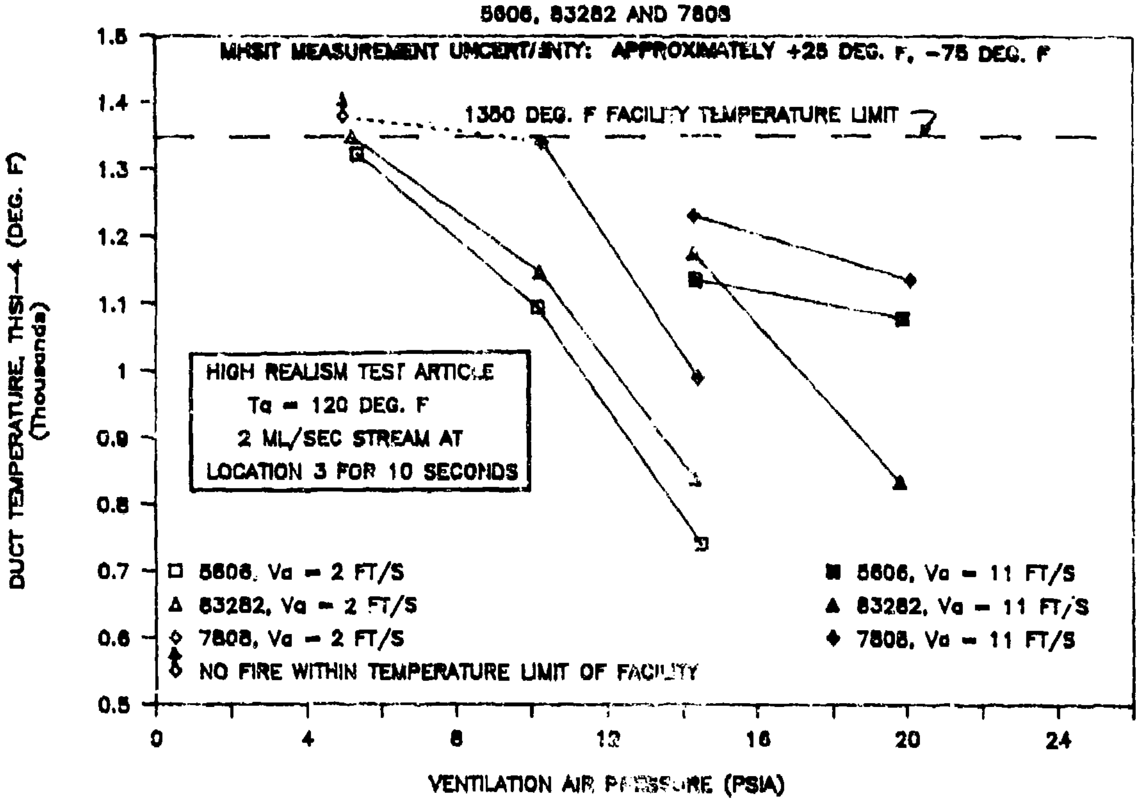


Figure 39. ***Effect of V_a on MHSIT for 5606; Upstream vs Downstream Spray***



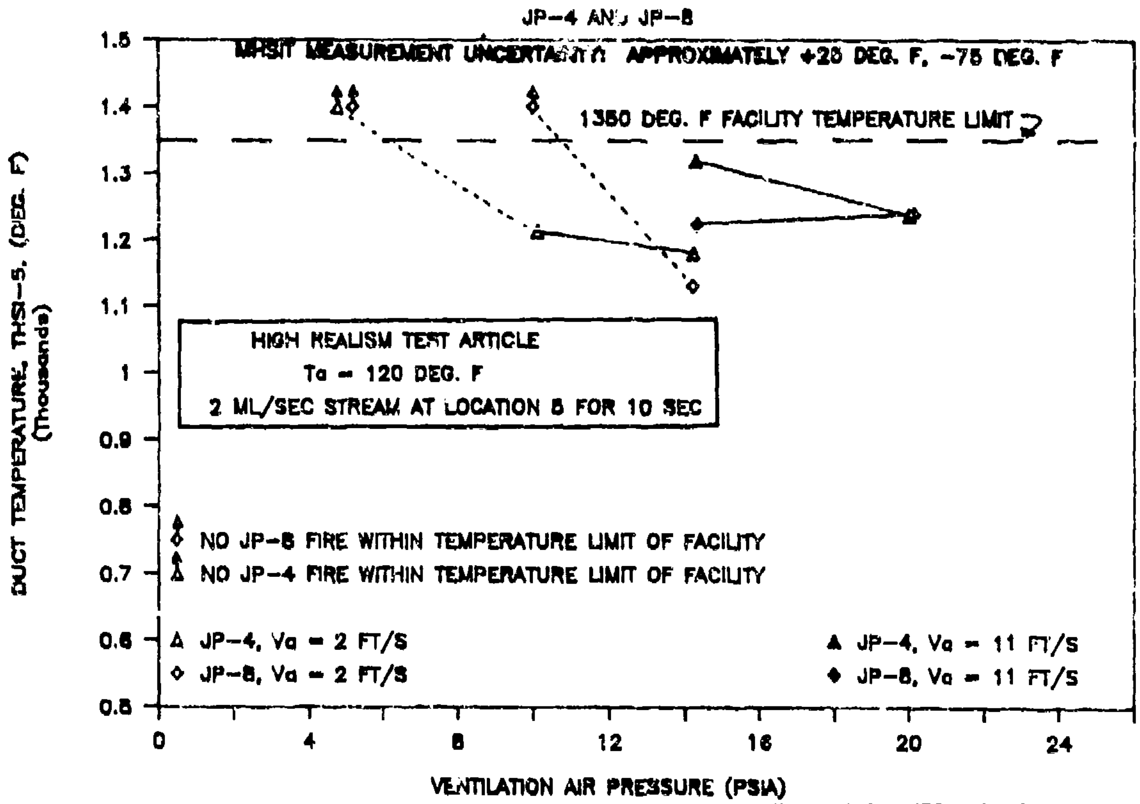


Figure 40. Effect of P_a on MHSIT with Fluid Stream

air pressure with a ventilation velocity of 11 ft/sec. The ventilation air temperature was held constant at 120°F for all of these tests.

With 5606, 83282 and 7808, unlike the tests employing spray from downstream, ignitions were obtained at air pressures below ambient as well as at ambient pressure and 20 psia. The MHSIT's of 5606 and 7808 were more sensitive to the pressure change below than above ambient pressure. The decrease in MHSIT for 5606 as ventilation air pressure was increased from 14.4 to 20 psia was only about 50°F while decreasing the ventilation air pressure below ambient affected the MHSIT much more strongly. Between ambient and 10 psia the MHSIT was increased 350°F; between 10 psia and 5 psia it was increased an additional 200°F. Similarly, for 7808 the change in MHSIT when ventilation air pressure was raised from 14.4 to 20 psia was not as large (100°F) as the increase in MHSIT when the ventilation air pressure was lowered from 14.4 to 10 psia (250°F).

The MHSIT of 83282 was affected by changes in pressure both above and below ambient pressure. Raising the pressure from 14.4 to 20 psia lowered the MHSIT from 1200°F to 850°F while lowering the pressure from 14.4 to 10 psia increased the MHSIT 300°F and decreasing the pressure further to 5 psia increased the MHSIT another 200°F. Since sprays of these fluids could not be ignited at pressures lower than ambient, these data indicate that the chance of hot surface ignition of fluids is greatly reduced at altitude when low pressures exist in a ventilated engine compartment.

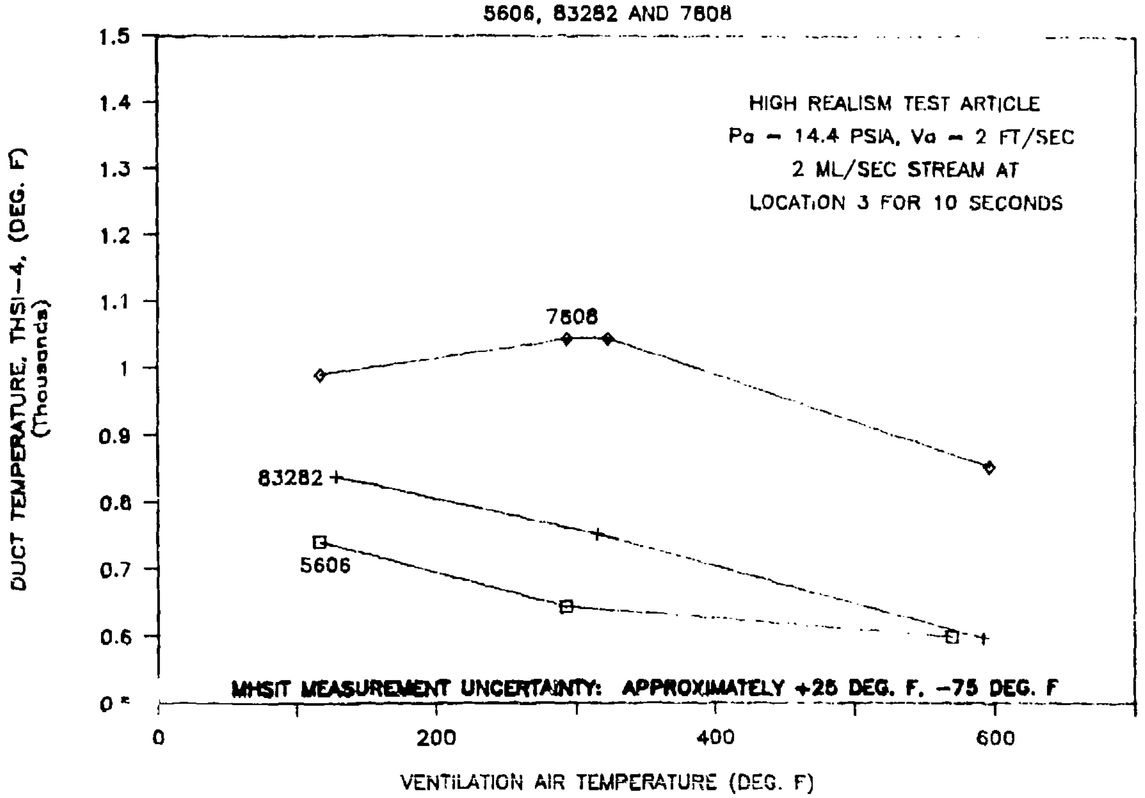
The effect of increasing the ventilation air pressure on the MHSIT of JP-4 and JP-8 was not as pronounced as the effect seen on the hydraulic fluids and the lubricating oil. The MHSIT for JP-8 actually increased slightly when the ventilation air pressure was increased from 14.4 to 20 psia but the increase was within the uncertainty of the temperature measurements (±25°F). When the ventilation air pressure was decreased to simulate altitude, JP-4 fires occurred at 10 psia, at a slightly higher duct temperature than at ambient, but did not occur up to the facility maximum of 1350°F at 5 psia. With JP-8, no fires occurred at either 10 or 5 psia, up to the 1350°F maximum available temperature.

Next, the effect of air temperature on the MHSIT of 5606, 83282 and 7808 stream at location 3 and JP-4 and JP-8 at location 5 was examined (Fig. 41). Ventilation velocity was set at 2 ft/sec and the ventilation air pressure was ambient (14.4 psia). The MHSIT of both 5606 and 83282 decreased with increasing ventilation air temperature, as anticipated, but the MHSIT for 7808 increased slightly as the air temperature was increased from 130°F to 300°F before being reduced substantially as the air temperature was increased to 600°F. This test at 300°F was repeated because these results were unexpected. The same results were obtained on the second try.

In this test 83282 was observed to ignite at a MHSIT of 600°F when the ventilation air temperature was 600°F. As in the earlier spray tests, this MHSIT was below the reported AIT for 83282. Again, this MHSIT was the last target temperature where ignition did occur prior to three tests where ignition did not occur. As with the spray tests with 600°F air, radiation losses led to thermocouple errors of about 60°F in these tests. Hence the air temperature was about the same as the fluid's AIT at the time of this last ignition.

Variation of the ventilation air temperature did not greatly affect the MHSIT of JP-4 and JP-8 streams. The JP-4 MHSIT remained almost constant for all air temperatures tested. The JP-8 MHSIT decreased and then increased as the air temperature was increased.

The effect of ventilation air velocity on the MHSIT's of the fluids injected as streams is shown in Figure 42. These tests were conducted at ambient pressure and at an air temperature of 120°F. Between 0 and 8 ft/sec, decreasing the ventilation air velocity seemed to have almost no effect on the MHSIT of 83282 while it did decrease the MHSIT's of 5606 and 7808. At a ventilation velocity of 8 ft/sec, the 83282 stream ignited at an MHSIT about 200°F lower than the 5606 stream. At 1 and 2 ft/sec the 5606 stream ignited at a MHSIT about 100°F lower than the 83282 stream. While the MHSIT's of JP-4 and JP-8 did increase as the airflow velocity was increased the effect was minimal.



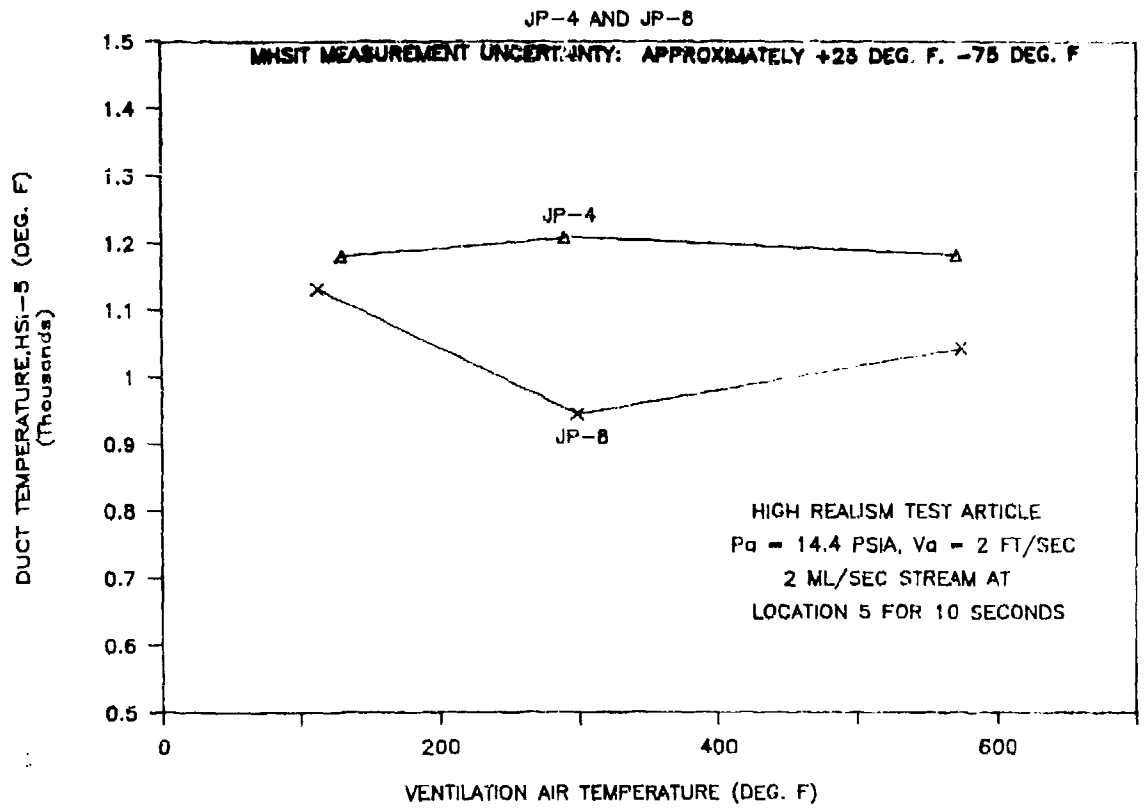
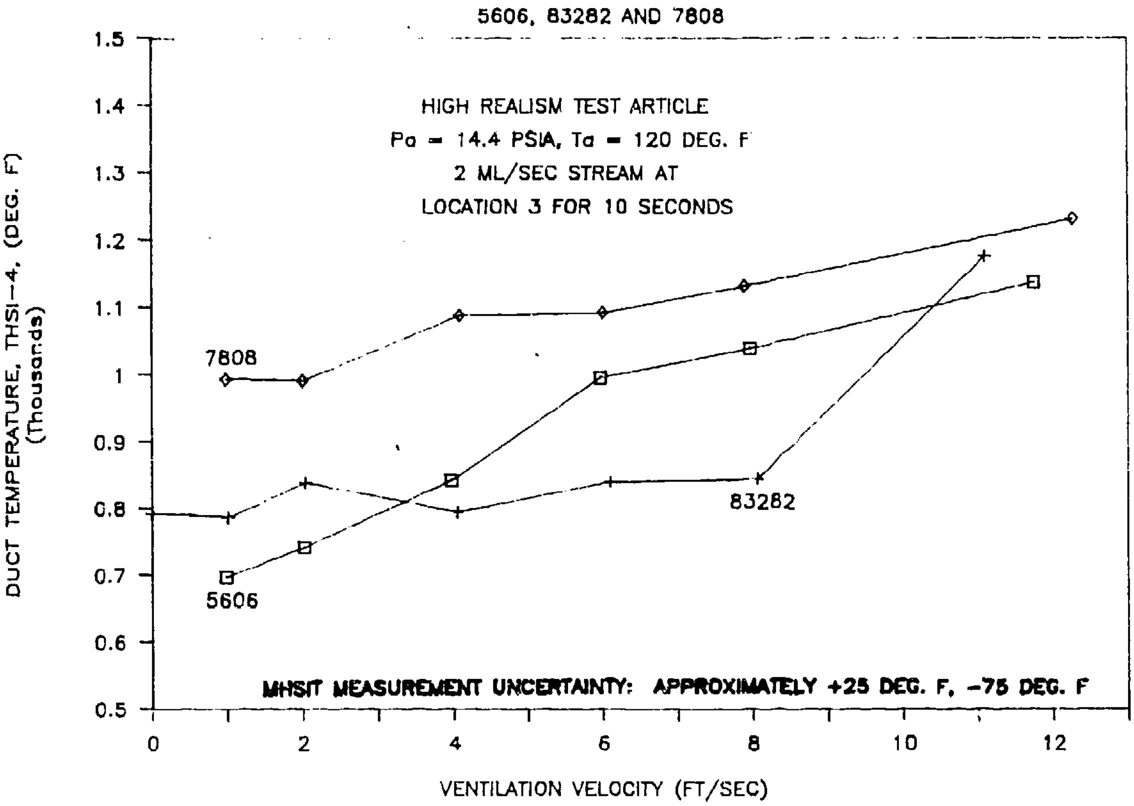


Figure 41. Effect of T_a on MHSIT with Fluid Stream



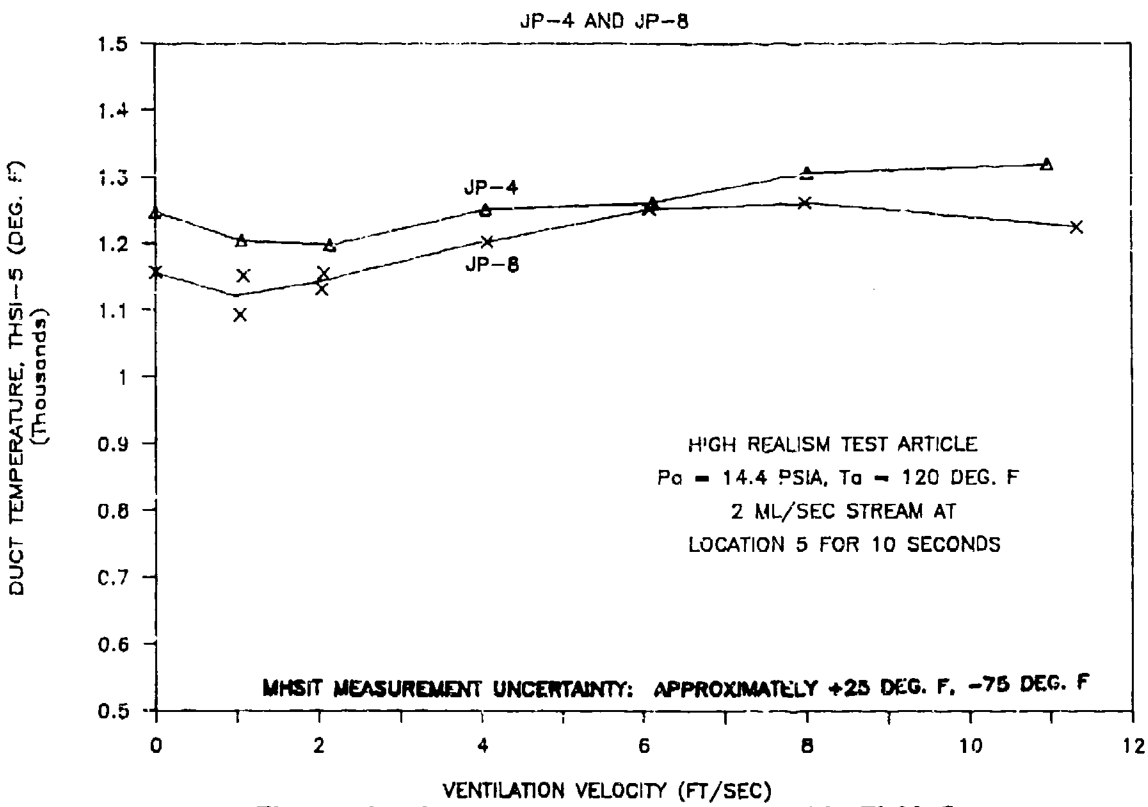


Figure 42. Effect of V_a on MHSIT with Fluid Stream

The effect of installing the baffle in the test article to reduce local airflow velocities around the bleed duct on the MHSIT's of all five fluids is shown in Figure 43. The MHSIT's with the baffle installed are significantly lower for 5606 and 83282 consistent with these fluid's MHSIT's sensitivity to velocity (Fig. 42). A much smaller reduction in MHSIT is seen with the baffle installed for 7808, JP-4 and JP-8, again consistent with the insensitivity of these fluids's MHSIT's to change in ventilation airflow velocity. Installation of the baffle reduced the airflow around the bleed duct enough that the hot bleed duct often heated the ventilation air (probably from 120°F to about 300°F) before injection could take place. Hence part of the cause of the lower MHSIT seen with the baffle in place was probably the elevation of the ventilation air temperatures.

4.2.2.3 Comparison of High Realism Stream vs. Spray

Test data acquired with stream and spray fluid introduction to the high realism test article was compared and differences in MHSIT due to the method of fluid introduction were examined. Stream injection of the fluid consisted of a solid stream from an 0.070 inch ID tube and traveled only about 0.5 inch before the stream contacted the bleed duct. In contrast, spray injection utilized a flat spray nozzle placed about 6 inches from the bleed duct.

The effect of ventilation air pressure on the MHSIT of the test fluids is shown in Figures 44 and 45. The MHSIT of 83282 for both spray and stream appears to be strongly affected by pressure. MHSIT's of 5606 and 7808 seem to be affected less. For these fluids, however, the MHSIT for stream injection at both 14.4 psia and 20 psia is lower than the MHSIT for spray injection at those pressures. This was consistent with the fact that sprays of neither fluid would ignite at the maximum (1350°F) duct temperature available at pressures below ambient while streams of both would. The MHSIT's of JP-4 and JP-8 were less affected by pressure. Again the MHSIT found with stream injection were lower than those found with spray.

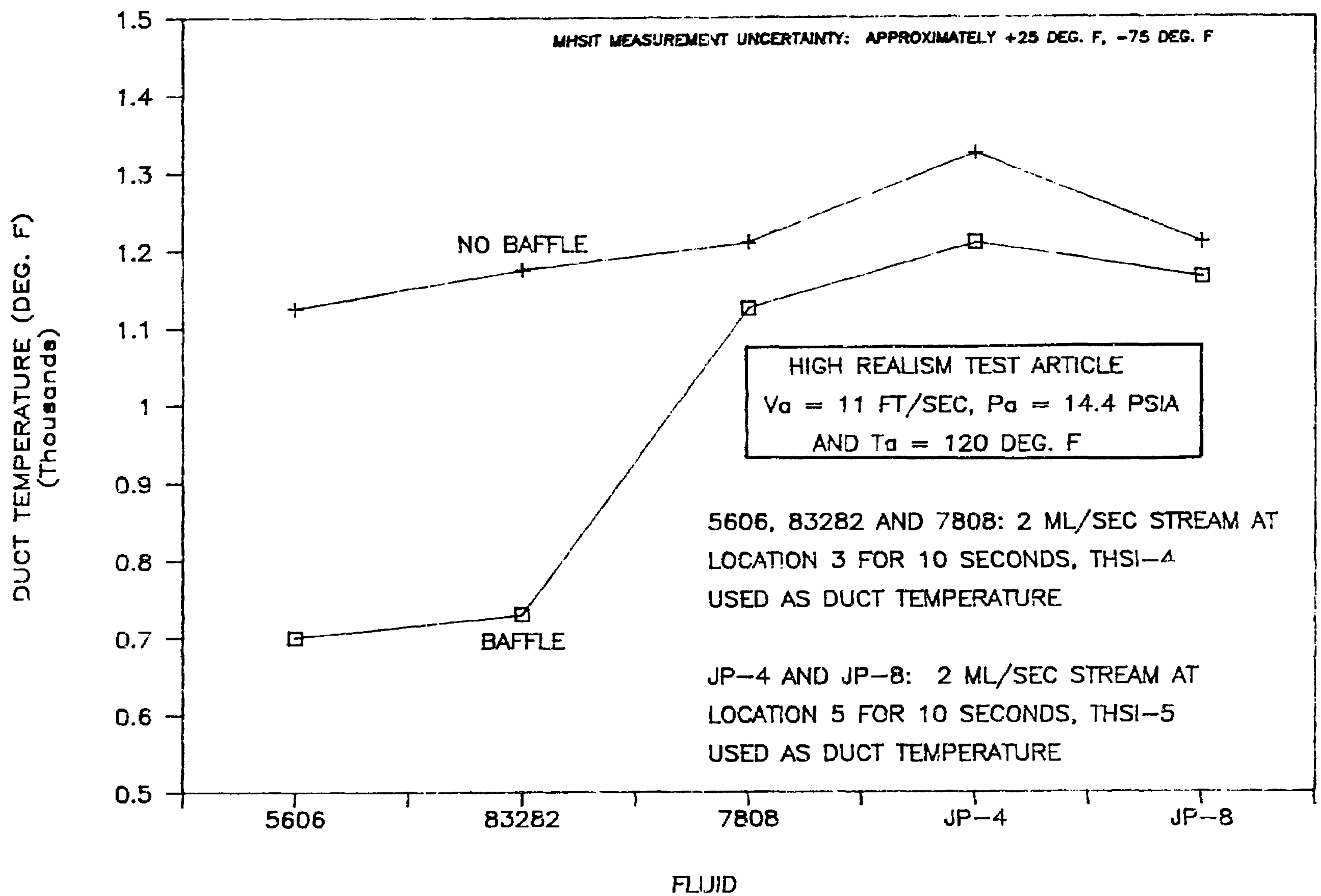


Figure 43. Effect of a Baffle on MHSIT with Fluid Stream

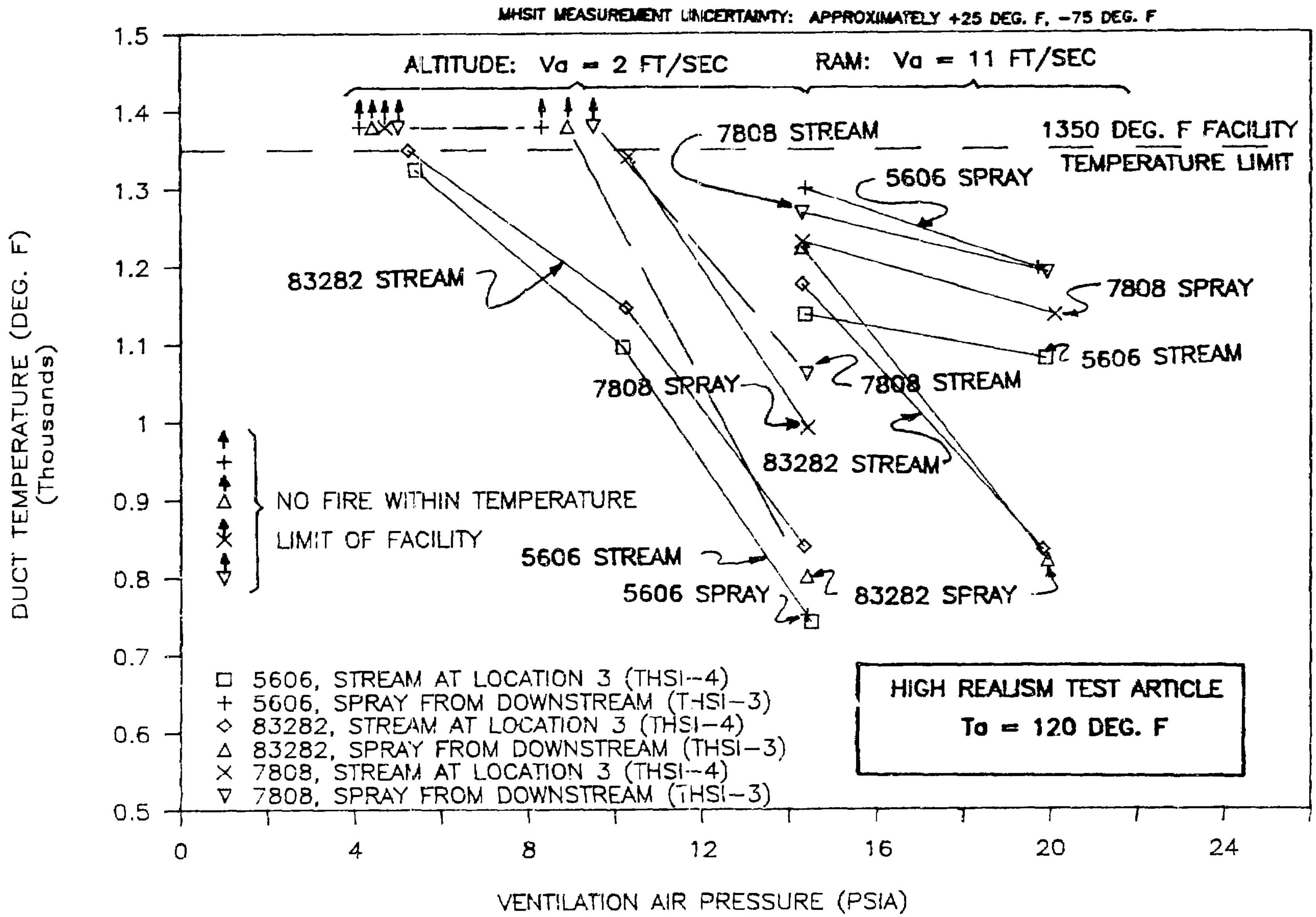


Figure 44. Spray vs. Stream at Location 3; Effect of P_a on MHSIT

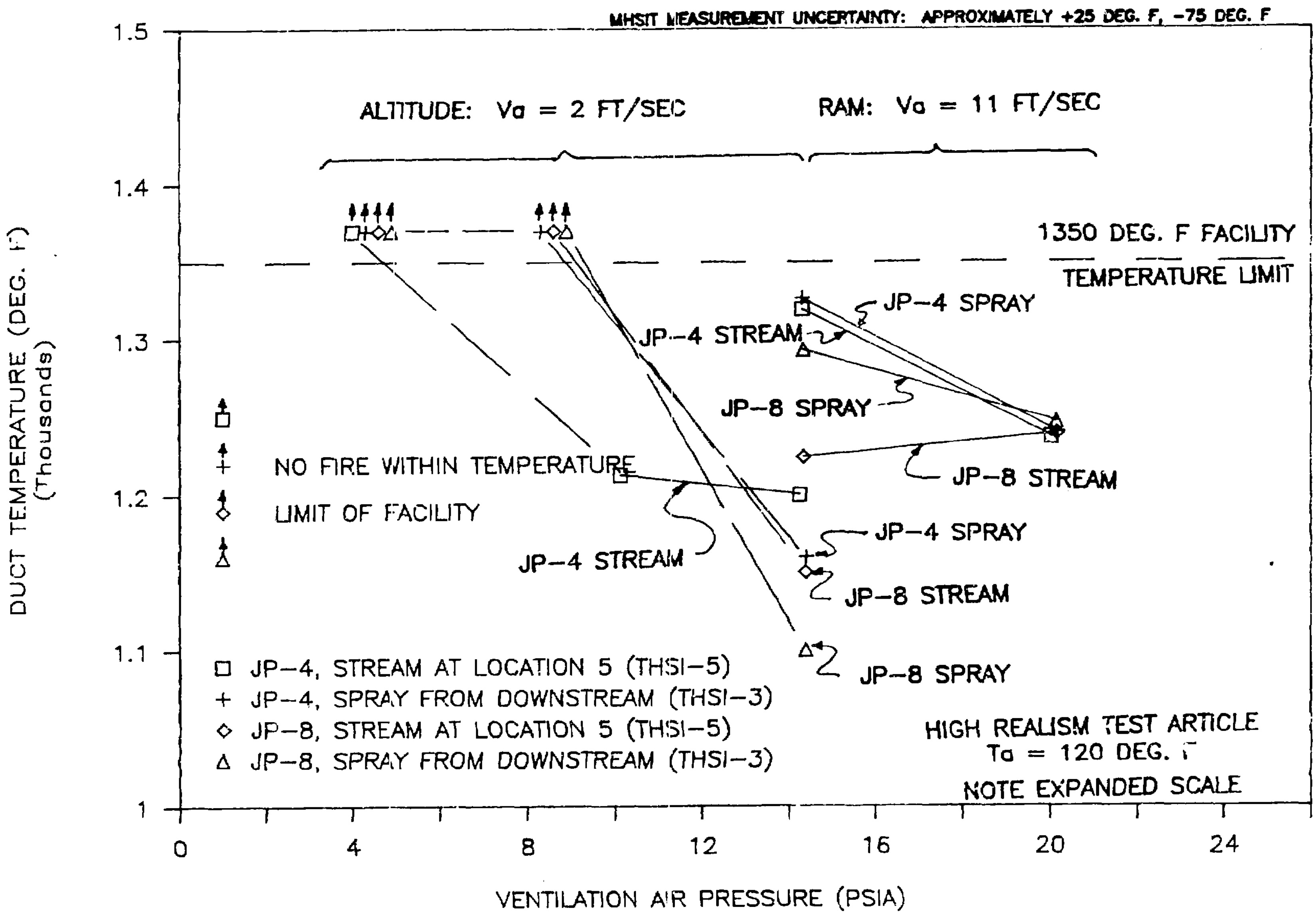


Figure 45. Spray vs. Stream at Location 5; Effect of P_a on MHSIT

Comparing the effects of air temperature variation on the MHSIT's of 5606, 83282 and 7808 (Fig. 46), data for both spray and stream show a tendency for the MHSIT to decrease with increasing temperature (excepting the 7808 MHSIT's at 120°F and 300°F) and no substantial differences are seen between spray and stream injection. In contrast, with JP-4 and JP-8 (Fig. 47), a large decrease is seen in MHSIT's for sprays as ventilation air temperature is increased and the MHSIT's obtained with streams are less affected. The MHSIT for JP-4 streams does not change at all as air temperature is increased, but the MHSIT for JP-4 spray decreases from about 1150°F when the air temperature is 120°F to about 750°F the air temperature is 600°F.

This difference between the two methods of fluid introduction is probably due to the small droplets of JP-4 spray being heated by the ventilation air and requiring less heat transfer from the bleed duct to reach ignition temperature. The fluid stream, however, is affected by the hot ventilation air only briefly before contacting the duct. The bleed duct provides most of the heat to raise the fluid streams's temperature to its ignition temperature. The JP-8 data is very similar, showing a large effect of air temperature on MHSIT for spray while a much smaller affect is shown for a fluid stream.

The effects of ventilation airflow velocity on MHSIT's for 5606 and 83282 with the two methods of fluid delivery are shown in Figure 45. MHSIT data for 83282 show minor differences between stream and spray. With 5606 the differences between stream and spray from downstream are also relatively minor, though the MHSIT's for spray from upstream are higher at all velocities tested. The effect of the velocity on the MHSIT for both injection methods is similar. A similar comparison of the two methods of fluid delivery for JP-4 and JP-8 is shown in Figure 49.

4.2.2.4 Comparison of High Realism and Simple Duct Results

A comparison of the MHSIT's measured for a spray delivery of 5606 and JP-4 acquired with the simple duct and the high realism test articles is made in Figure 50. The simple duct test article data includes MHSIT's for the

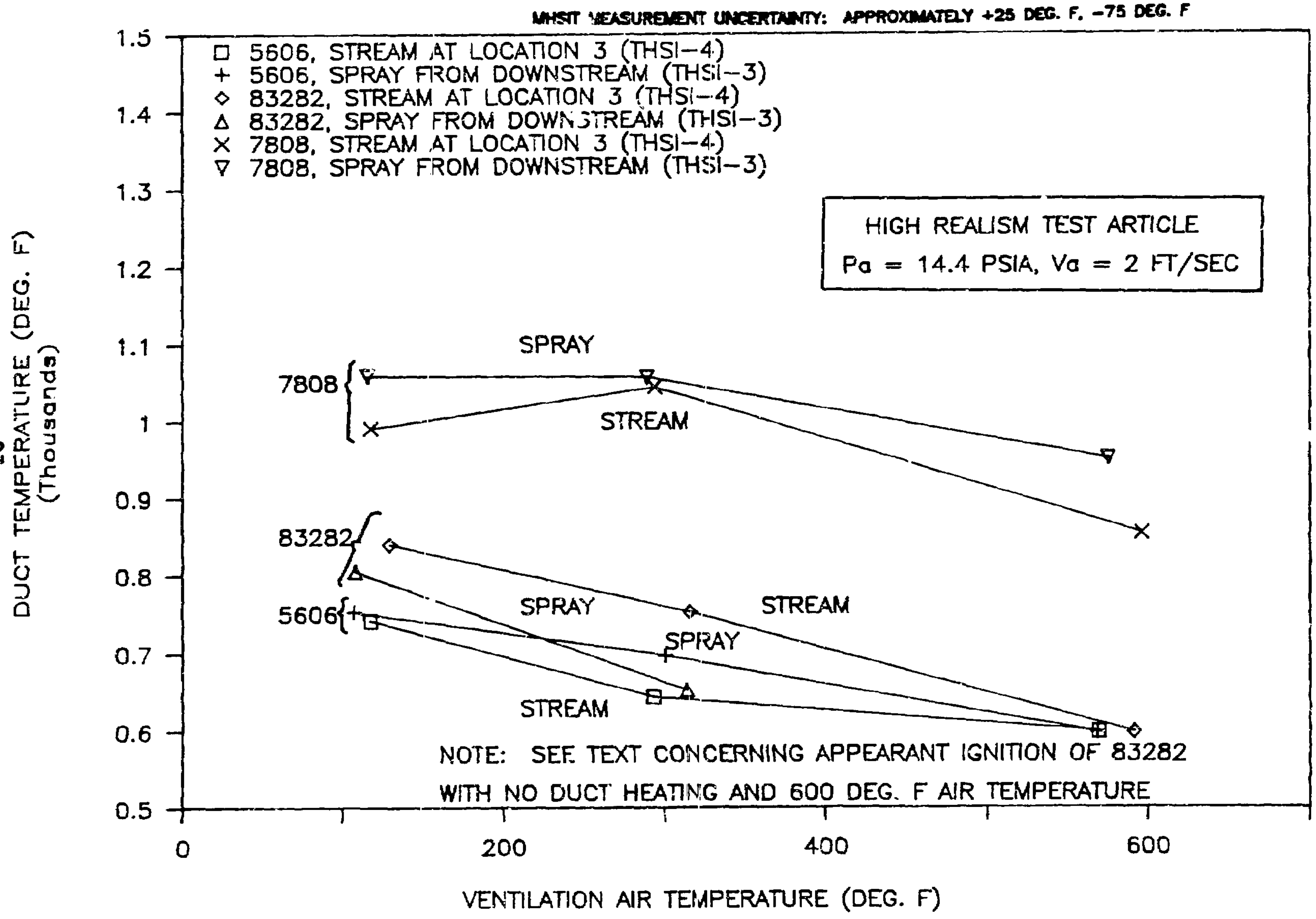


Figure 46. Spray vs. Stream at Location 3; Effect of T_a on MHSIT

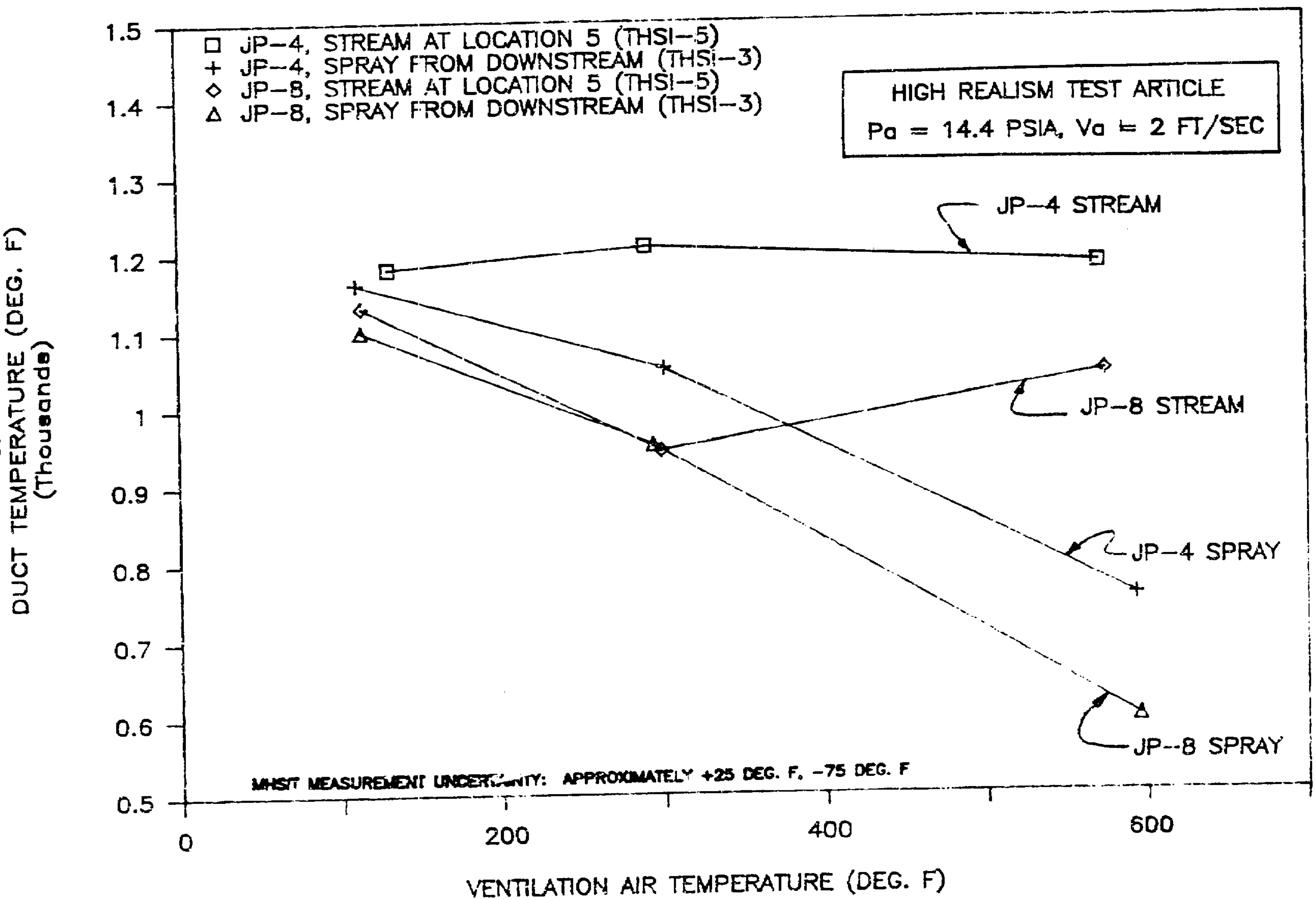


Figure 47. Spray vs. Stream at Location 5; Effect of T_a on MHSIT

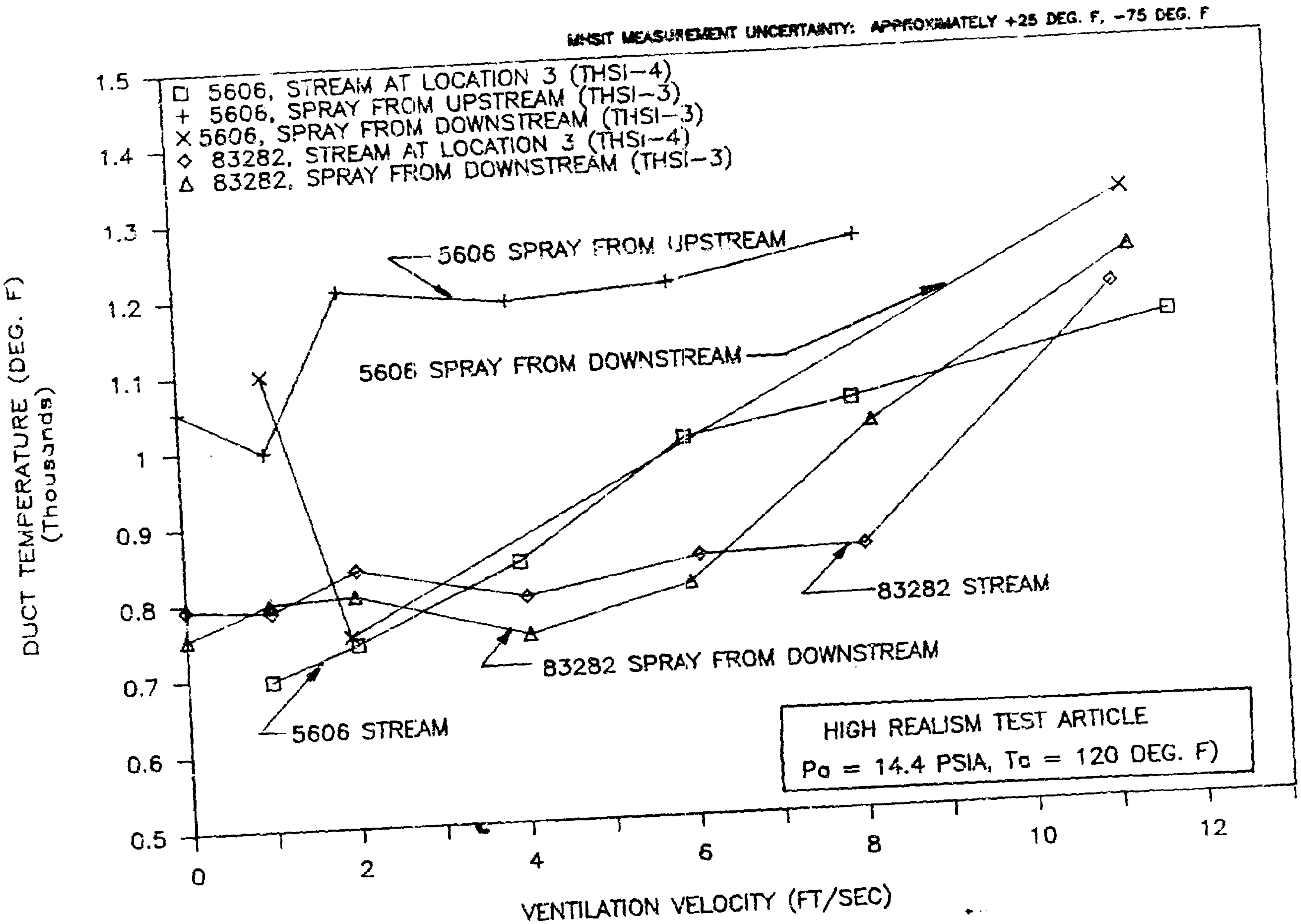


Figure 48. Spray vs. Stream at Location 3; Effect of V_a on MHSIT

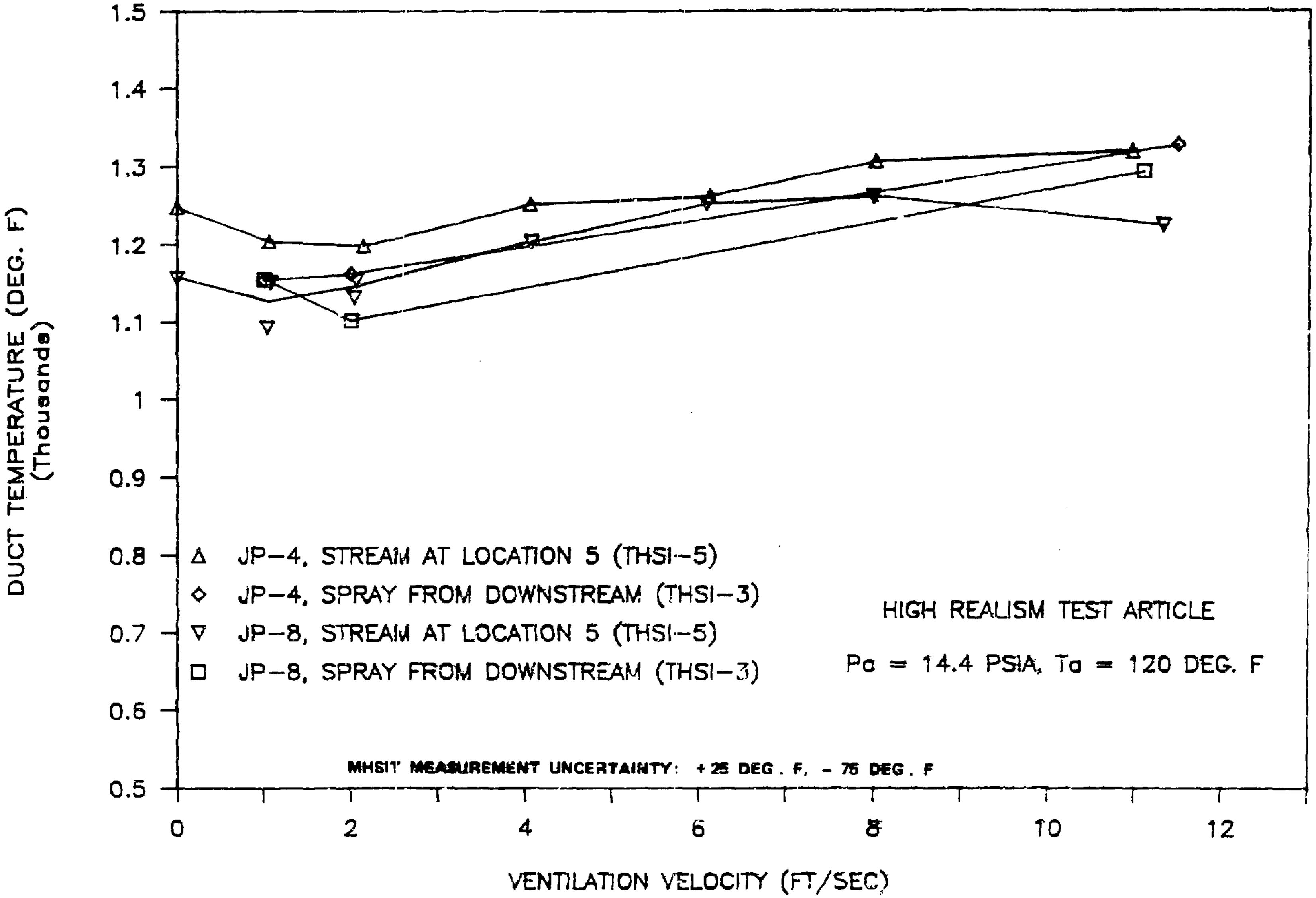
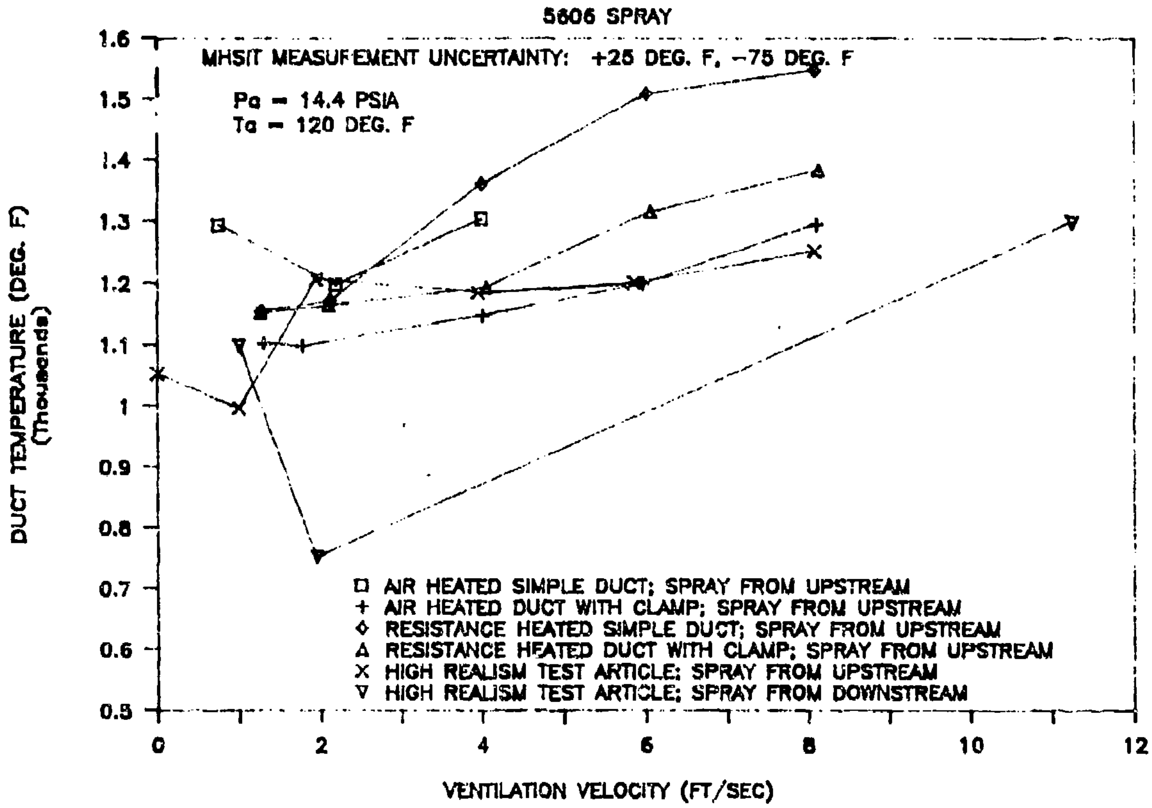


Figure 49. Spray vs. Stream at Location 5; Effect of V_a on MHSIT



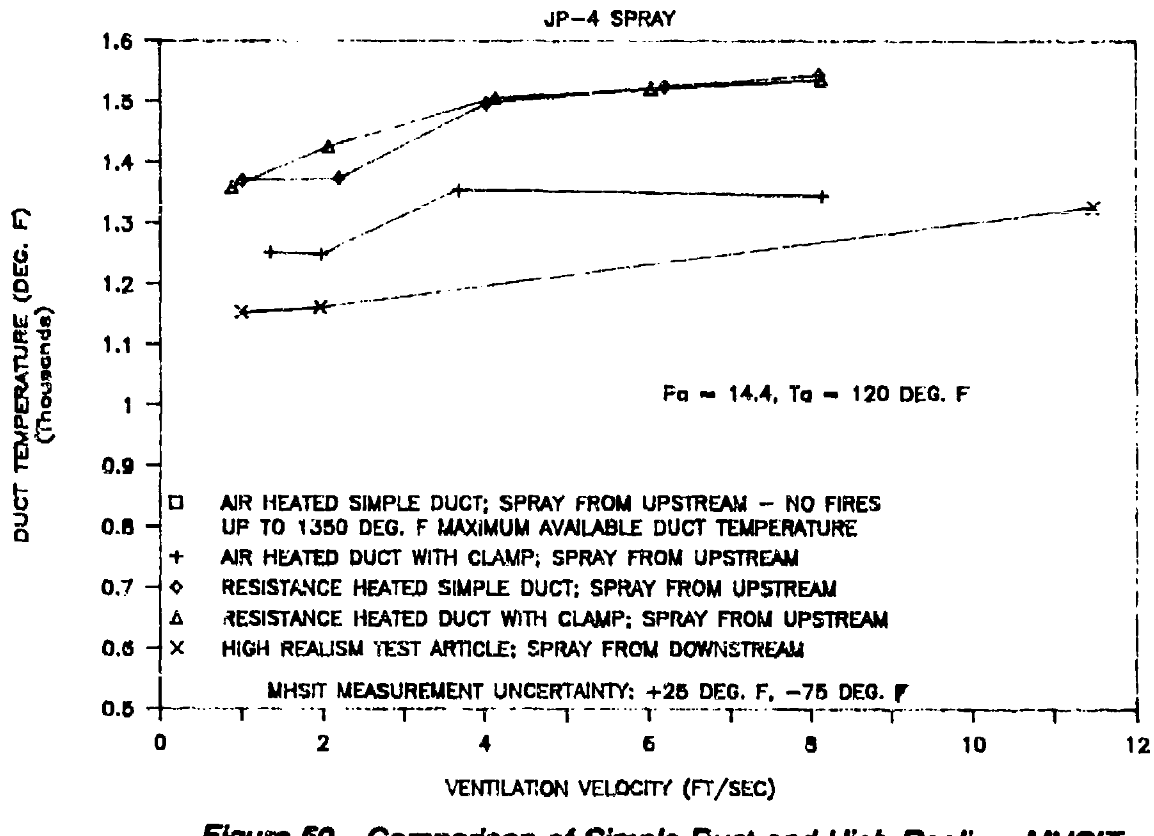


Figure 50. Comparison of Simple Duct and High Realism MHSIT

bare duct and the duct with clamp with both air and resistance heating. MHSIT data for a similar spray onto the high realism test article is included for comparison. With the 5606 spray, the upstream spray high-realism test article data agrees best with the air-heated simple duct with the cushion clamp data. The downstream spray high-realism data acquired at 2 ft/sec, however, indicates a MHSIT about 250°F lower than any of the other tests.

With the JP-4 comparison shown on Figure 50, the downstream spray high-realism test article data again indicates lower MHSIT's than any of the simple duct tests. The difference is smaller than with 5606, however, about 100°F.

4.3 Summary of Results

4.3.1 Simple Duct

1. The bare duct ignited 5606 at higher temperatures than when a cushion clamp was added. This was probably due to the clamp holding the fluid next to the hot duct for a longer time, allowing more heating of the fluid. The addition of a the clamp did not affect the MHSIT for JP-4 spray onto the resistance heated duct, however. JP-4 being more volatile, probably vaporized almost immediately with or without the clamp and was not held against the duct longer by the clamp. Because no ignition occurred when the JP-4 was sprayed onto the air-heated bare-duct at the maximum duct temperature available but did when the clamp was added, it appears that the addition of the clamp to the air-heated duct lowered the MHSIT for JP-4.

2. Lower MHSIT's for both JP-4 and 5606 were generally measured with the air-heated duct than with the resistance heated duct. This was probably mostly due to the higher heating rate available with the air-heated duct.

3. The MHSIT of 5606 showed a strong dependence on the ventilation velocity, increasing 200°F to 400°F when the ventilation velocity was

increased from 1 to 8 ft/sec. JP-4's MHSIT was not as affected by velocity.

4. At low ventilation velocities, the MHSIT for 5606 was about 200°F lower than the MHSIT for JP-4 whether measured with the resistance or air-heated duct. At ventilation velocities of 6 to 8 ft/sec the MHSIT's of the two fluids were about the same.

5. Whether the simple duct was oriented vertically or horizontally had a significant effect on the MHSIT for 5606. When the duct was placed in a vertical position no fires were ignited with the duct heated to the maximum temperature available, at any ventilation airflow velocity.

4.3.2 High Realism

1. The injection location was found to strongly affect the MHSIT's in the high realism tests. A variety of factors, including the local ventilation air velocity and temperature and the heat transfer coefficients of the particular fluid contact site on the duct affected what MHSIT was determined for the fluid. It was found that a stream onto a horizontal bare section of the duct ignited 5606, 83282 and 7808 at the lowest temperatures. It was found that a stream onto a horizontal section of the duct, where a clamp was located, ignited JP-4 and JP-8 at the lowest temperatures. It was also found that spray from downstream also ignited 83282 at a relatively low temperature. For the range of spray and stream flowrates that were investigated, little effect of injection flowrate or duration was observed.

2. The MHSIT's of all five test fluids, both spray and stream, increased dramatically as ventilation air pressure was lowered. Hence, MHSIT'S are significantly increased for aircraft at altitude.

3. The MHSIT's of all five fluids generally was decreased as the ventilation air temperature was increased. The MHSIT of 7808, however, was affected only slightly. With an air temperature of 600°F, the MHSIT of 83282 (spray and stream) was below the fluid's AIT.

4. For all fluids the MHSIT for both spray and stream was higher at a velocity of 8 ft/sec than at a velocity of 1 ft/sec. The MHSIT's of JP-4, JP-8 (spray and stream) were effected only slightly by velocity, however.

5. The effect of ventilation air temperature on the MHSIT of JP-4 and JP-8 was different for spray and stream fluid introduction. High ventilation air temperatures dramatically decreased the MHSIT of JP-4 and JP-8 spray while effecting the MHSIT's for stream introduction only slightly. This was probably because the spray droplets were preheated in heated air before they made contact with the hot duct while the fluid stream had less time for preheating before it struck the hot surface.

6. In general, the hydraulic fluids, 5606 and 83282, tended to ignite at lower MHSIT's than the JP-4 and JP-8 fuels. Lubricate 7808 was somewhere in between for the majority of the test conditions.

7. Both fluid injection modes, spray and stream, are important in determining the lowest MHSIT depending on test conditions and the type of fluid.

8. The high realism test article with its associated clutter gave lower values of MHSIT than the simple duct test article. This difference may have been even greater if the AENFTS test section had been horizontal during testing with the high realism test article.

9. The reported MHSIT's may be up to 75°F higher than actual values due to test technique and measurement error and the MHSIT's may have been lower if the AENFTS test section had been installed in its horizontal position.

10. To determine the maximum safe design temperature, the highest operational compartment temperature and pressure should first be established. At these conditions, the lowest MHSIT, independent of ventilation airflow, should be noted for each fluid of interest after examining experimental uncertainties and both injection modes, spray and stream. The lowest value of MHSIT resulting from the above procedure

should then be reduced by at least 150°F to arrive at the maximum safe design temperature. (Note: Elevated fluid temperatures and large hot surfaces (engine case) were not considered in the above suggested reduction of at least 150°F)

4.3.3 Test Article, Facility and Technique

1. The AENFTS provides a realistic simulation of the airflow conditions affecting hot surface ignition in and aircraft engine compartment. The facility's inability to simulate a full range of altitude conditions is of relatively little importance because the altitude conditions were found to reduce hot surface ignition risk.

2. The F-16 nacelle simulator, with its realistic clutter (providing regions of stagnation as well as regions of high velocity) and its real aircraft engine bleed duct, allowed tests to be conducted which closely duplicated real aircraft engine compartment conditions without the cost and safety problems which would be encountered trying to conduct fire tests in a real aircraft.

3. The Graviner UV optical fire detector unit which was employed with both the simple duct and the high realism test articles continued to perform throughout the entire test program without problems. Because its intended 1 second response time tended to be slower than the test operator's visual response to the fire on the console video monitor it was not normally the first indication that a fire had ignited. During some situations, however, where the fire was small, or the viewing window was obscured by soot, it was the first indication observed. No change in its sensitivity was observed during this program--even when compared to its performance when first installed in the AENFTS in 1984.

5.0 ANALYSIS AND INTERPRETATION OF THE RESULTS

In this section the main findings presented in Section 4 are analyzed and interpreted in light of the key processes involved in hot surface ignition. To do this, reference is made to the preliminary and approximate analyses of sprays and streams, presented in Appendices D and E, respectively. These analyses were formulated specifically to help identify the relative importance of various concurrent processes and their contributions to the test results. Also, they form a basis on which modeling effort can be carried out in the future.

5.1 Spray Analysis

Appendix D presents a simplified characteristic time analysis for the major processes involved in the hot surface ignition of sprays. These processes include atomization, droplet translation and deceleration, gas phase heat transfer in the duct boundary layer, droplet heating and vaporization and chemical kinetics of the ignition reactions.

For simplicity, the analysis focuses on the case of a single bare duct instead of the complex geometry of the high realism tests. Also, no attempt was made to calibrate the analysis using test data. Thus, the analysis is very crude, but still, it allows approximate predictions of minimum hot surface ignition temperatures, MHSIT's. As expected, the numerical predictions are not accurate, but the predicted trends are in reasonable agreement with test data in most cases. Furthermore, the analysis identifies the relative importance of the various processes thus enabling interpretation of the results.

5.1.1 Predicted Droplet Behaviors for the Five Fluids

Illustrative results comparing the droplet behaviors for sprays of the 5 fluids are shown in Table 11. Note that:

- for JP-4 and JP-8, the (volume to surface or Sauter) mean diameters of the droplets produced in the spray are of the order of 50 microns. These small droplets decelerate quickly before reaching the duct and then are entrained by the ventilation air.

- for 5606, 83282 and 7808, the droplets are much larger (in the range of 180 to 250 microns) mainly because of the higher viscosities of these fluids. These larger droplets decelerate more slowly and impact the duct at a high velocity and high Weber number (suggesting that these droplets may shatter upon impact.)

- concomitantly, the time required for droplet evaporation (due to gas-phase heat transfer) is much shorter for the lighter fluids (of the order of 10 ms versus 100 to 1000 ms for the heavier fluids).

Thus, there is theoretical evidence that droplets from sprays of the heavier fluids may accumulate on the duct forming a thin liquid film that boils on the surface, approaching the situation of a stream. Thus, in so for as processes in the liquid phase, difference between the behavior of spray vs. stream should be less accentuated for heavier fluids than for lighter fluids (other things being equal).

5.1.2 Measured vs. Predicted Trends in MHSITs for the Jet Fuels

In Section 4, the results of a systematic study of the effects of ventilation air parameters (pressure, P_a, velocity, V_a and temperature, T_a) on the MHSIT's of the five fluids under the high realism test conditions were presented. These results are compared below with our predictions for JP-4 and JP-8 (for which a complete set of fluid

Table 11. Illustrative Results for Spray Analysis

ITEM		JP-4	JP-8	5606	7808	83282
----		----	----	----	----	----
DROPLET FORMATION -- Nozzle 621, 0.021" diam., 8 cc/s, 117 psig						
Liquid density,	g/cc	0.76	0.81	0.88	0.95	0.85
Surface tension,	dyne/cm	22	23	32	30	30
Absolute viscosity,	g/cm.s	0.01	0.01	1.15	2.30	4.57
Sauter diameter,	micron	48	54	177	206	248
Initial Droplet Reynolds No.		89	101	330	384	462
DROPLET DECELERATION --	Ventilation air = 4 ft/s @ 120°F, 14.4 psia nozzle @ 1 ft from duct					
Deceleration length , cm		6	8	54	73	86
Deceleration time, ms		2	2	15	21	25
Time of duct impact, ms		204	189	21	16	14
Velocity at impact, cm/s		122	122	613	1145	1425
% Deceleration at impact		100	100	86	71	63
Transit time near duct, ms		31	31	6	3	3
End of heating time, ms		235	220	28	19	17
Weber number at impact		2	3	185	855	1428
HEATING/EVAPORATION ANALYSIS --		Duct Temperature =		1135 Deg. F		
Boiling Pt., Deg. C		99	192	244	293	432
Molecular weight,	g/gmole	125	167	266	425	400
Latent heat, H_{fg},	J/g	211	229	204	357	105
Specific heat	J/g(Deg.C)	2.06	1.95	2.19	2.19	2.19
H_{fg} eff.,	J/g	375	565	694	955	1007
Mass transfer (B) number		1.06	0.52	0.35	0.23	0.11
Droplet Reynolds in duct BL		0	0	13	31	48
Nusselt No		2	2	4	5	6
Evaporation time,ms		7	16	254	488	1343
				(a different heat transfer mechanism may apply here)		
KINETICS OF IGNITION						
Activation Energy	cal/mole	43060	37780			
Frequency factor	ms/atm**n	1.17E-09	1.68E-08	not found in literature		
Reaction order, n		2	2			
Chemical time, ms		24	19			
IGNITION CRITERIA						
(Evap+Chem)/transit time		0.97	1.10			
Is there sufficient time?		yes	no			

properties was found in the literature. Similar comparisons for the other fluids cannot be presented because kinetic data for their ignition reactions could not be located. See Appendix C).

The high realism tests are more complicated than this simplified analysis. Trends in the dependance of the MHSITs on ventilation air parameters can be observed (Figs. 50 to 52). Note that:

- In Figure 51, MHSIT decreases with increases in P_a mainly due to the reduction of the time required for completion of the chemical reaction associated with ignition. Although, the trend is correctly predicted for both JP-4 and JP-8, the agreement between predicted temperatures and measurements is much less for JP-8 than JP-4. Clearly, the analysis needs improvement.

- In Figure 52, MHSITs decreases with increase in T_a, which is also due mainly to a decrease in the chemical reaction time. To account for this effect, it is assumed for simplicity that the reaction temperature in the duct boundary layer increases by one half of the air preheat temperature (over ambient). This is a standard assumption in the literature. Similar trends are observed for both test data and theory.

- In Figure 53, MHSIT increases with increase in V_a mainly due to a reduction in the transit time available for heating, and a need for a higher temperature so that ignition occurs within the shorter time. (The data shown in this figure are for JP-4 sprayed on a simple duct with clamp. At the time the analysis was carried out, this was the only test conditions for which there was data that could be compared with the analysis on a V_a-MHSIT plot.)

Note: an initial dip in the MHSIT-V_a relationship was observed at a low V_a (0 to 1 ft/sec) in the early tests on a simple duct with 5660. It may be attributed to the trajectory of the droplets near the duct as a function of the relative magnitude of the ventilation velocity (V_a) and the natural convection velocity (V_n) around the hot duct. When V_n dominates over V_a,

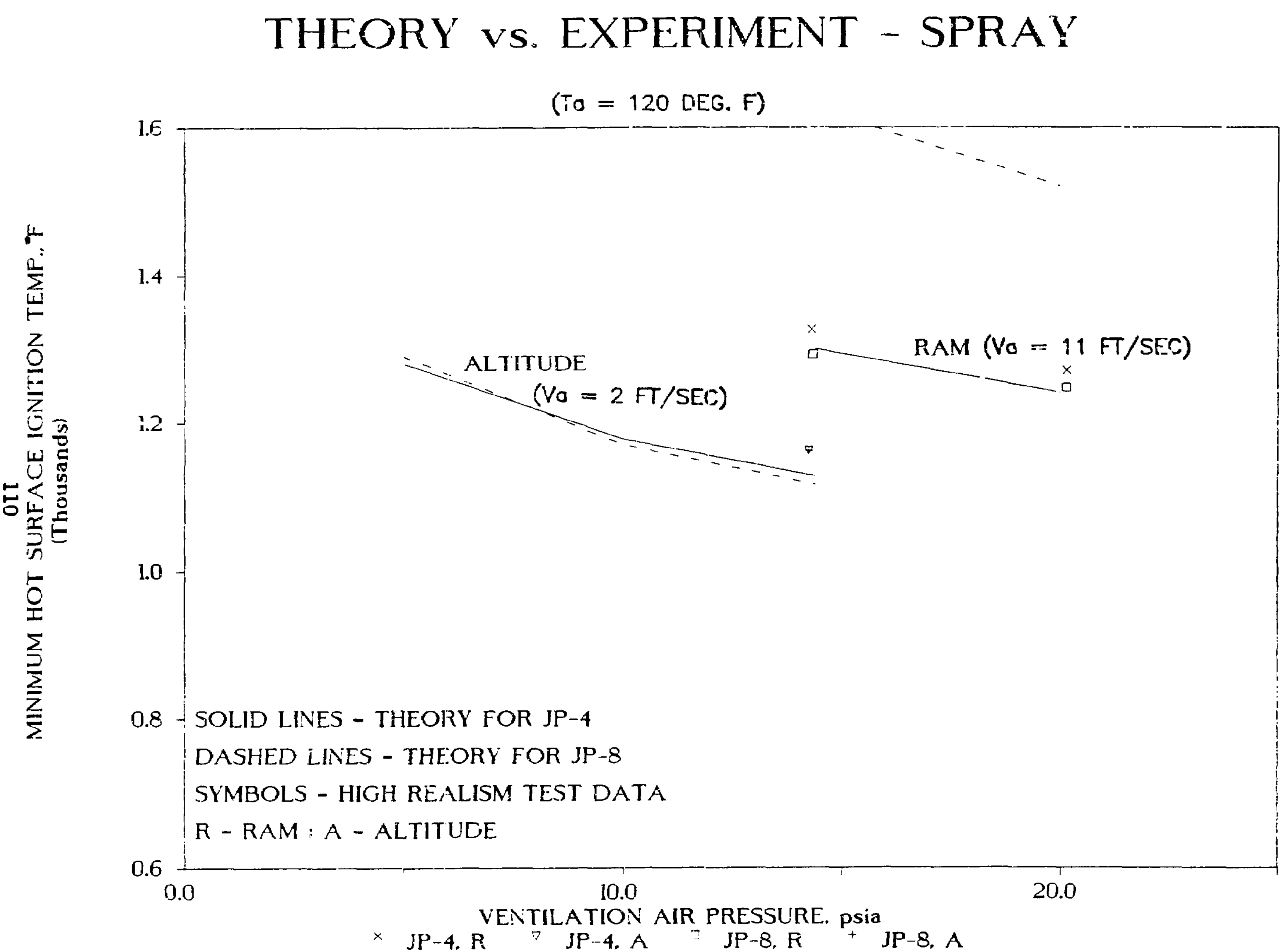


Figure 51. Effect of Air Pressure on MHSIT; Theory and Experiment

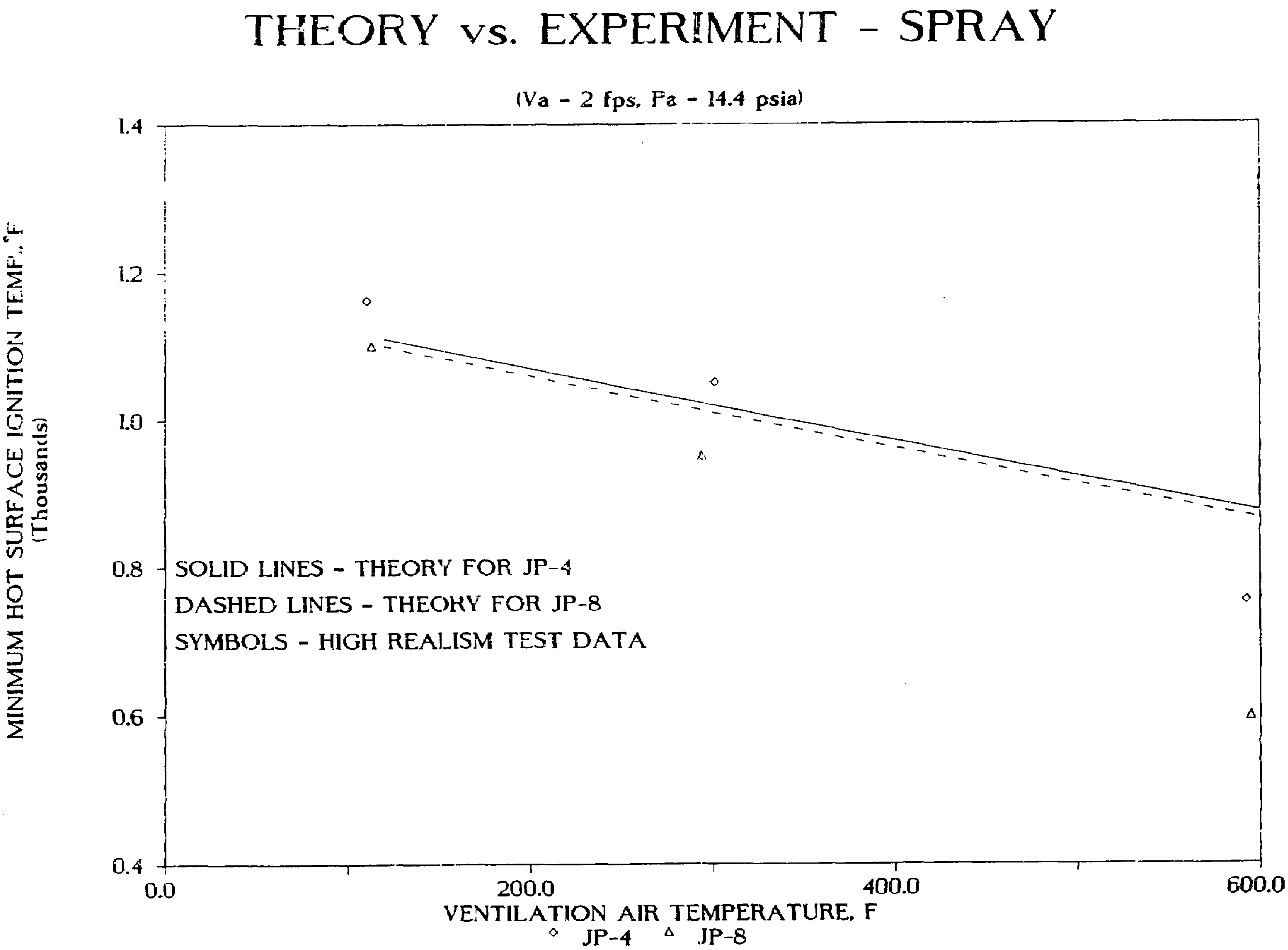


Figure 52. Effect of Air Temperature on MHSIT; Theory and Experiment

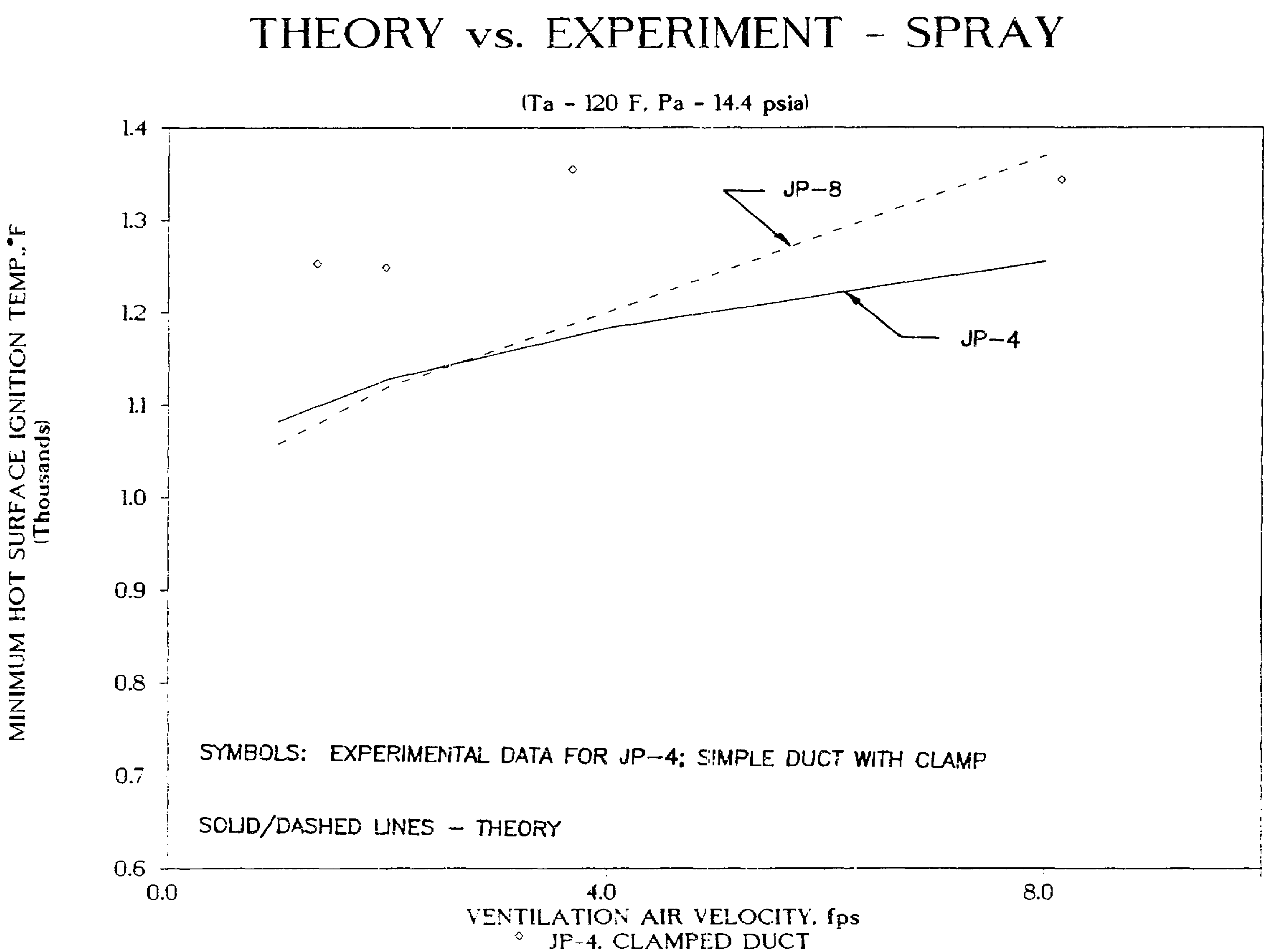


Figure 53. Effect of Air Velocity on MHSIT; theory and Experiment

only larger droplets will reach the surface (while the smaller ones will be entrained above and away from the duct in the natural convection plume around the hot duct). Since V_n is of the order of 1 to 3 ft/sec, this effect is anticipated at $V_a \approx 0$ to 2 ft/sec and should disappear at higher V_a.

Also, note: The analysis predicts that higher MHSITs are required with larger droplets, although the effects of V_n is not included (explicitly) in the analysis such inclusion is recommended in future work.

5.2 Stream Considerations

In the stream tests, the fluid is injected by a drip tube onto a horizontal section of the hot duct. The fluid stream impacts the duct and spreads radially while boiling due to heat transfer from the duct surface. After a very short distance, the spreading fluid breaks up into rivulets. The rivulets continue to flow over the duct and further break up to smaller sizes. (See Plate E-1 in Appendix E) Once vapors are formed, the remaining processes (mixing with air, further heat up of the mixture and chemical reactions) are essentially similar to the case of a spray.

Key unknowns in analyzing the above situation are the details of the boiling phenomenon, a very complex subject even for non-reacting fluids.

Key questions include:

- o is boiling in the nucleate or film regime?
- o are the liquid and vapor saturated or not?
- o what are the effects of fluid properties and nacelle pressure?

Depending on the answers to these questions, large differences are expected in the rates of fluid evaporation and the attained temperatures, which in turn would effect the MHSIT results of this study.

To answer the above questions, first, an attempt was made to measure the temperature time history at the duct surface immediately below the injection point of a stream. The measurement was not successful because of the clutter in the nacelle. (This should be done in the future on simple duct-type experiments).

Second, the literature was searched for data on the boiling behaviors of aircraft fluids of interest. No directly pertinent data for either the above configuration or even the simpler case of a boiling liquid pool was found. Accordingly, estimates were made of the boiling regimes for each fluid and for the test conditions in this study (by indirect means as presented in Appendix E).

The results are very approximate and require direct verification in future work. Still, they suggest the following physical picture for the case at hand. As liquid flows over the hot plate, its temperature rises but the fluid remains subcooled. Vapors are formed only very near the surface where a very thin layer of fluid reaches the saturation temperature. The vapors rise through and condense in the liquid. The applicable regimes appear to be mainly subcooled film boiling for all the fluids of interest except for 83282, where subcooled nucleate boiling and liquid wetting of the duct also occurs. (See Figs. E-3 to E-7 in Appendix E).

At the edge of the spreading liquid film, the produced vapors exit the duct/liquid interface and are available for mixing with air and for ignition. Because of proximity to the hot duct, the exit temperature of these vapors (from the interface) may be larger than the saturation temperature of the fluid (i.e., the vapor superheats under the liquid). Various correlations were tried based on this physical picture, but the results were not successful. Clearly, this subject deserves further study in the future.

5.3 Discussion of Spray Vs. Stream Results for the Five Fluids

Drawing upon the point of view presented in Sections 5.1 and 5.2, the major mechanistic differences and similarities between sprays and streams include:

- o differences in the mechanism of heat transfer from the duct to the liquid, namely, gas phase conduction, and boiling at a hot surface for sprays and streams, respectively. These mechanisms have different dependencies on the ventilation parameters that can be reflected in the MHSIT data.

- o similar gas phase kinetics reactions regardless of spray or stream. Thus, the effects of ventilation parameters via chemical kinetics are expected to be similar. Consequently, the discussion of the effects of these parameters on sprays in Section 5.1 also applies qualitatively to streams.

- o under some conditions, a spray may produce a thin liquid film on the duct surface, approaching the situation of a stream as described in Section 5.1.1.

Against these theoretical considerations, the results of the systematic study of the effects of ventilation parameters on the MHSITs for the five fluids for both sprays and streams is discussed below. Note that there are other processes which may come into play that are too numerous to mention. Also, the three items listed above may take place concurrently in a given test with reinforcing and/or competing effects. Thus, the discussion can only be suggestive and qualitative. More detailed testing and analysis is required to support the discussion on firmer ground.

<u>Effect of Ventilation Air Temperature, T_a</u>

For the heavier fluids (5606, 83282 and 7808), the effects of T_a on MHSITs are about the same (within 100^oF) whether the fluids are injected as a stream or a spray (from downstream). Also, MHSIT decreases moderately with increase in T_a. (Fig. 46).

On the other hand, for the lighter fluids (JP-4 and JP-8) the corresponding effects differ significantly (up to 450°F) for a spray versus a stream: MHSIT decreases strongly with increase in T_a for sprays and moderately to negligibly for streams. (Fig. 47).

The above effects can be explained as follows: a higher T_a promotes faster gas-phase heat transfer but has little effect on boiling heat transfer, with a concomitant greater reduction of the MHSIT for sprays than for streams as observed for the lighter fluids. In the sprays of heavier fluids, a liquid film is produced on the duct and hence their behavior is more like a stream than spray.

Effect of Ventilation Air Pressure, P_a

The effect of decreasing the pressure, to simulate increasing altitude, is generally an increase of the MHSIT as shown in Figures 44 and 45. Also, the effect of increasing the pressure to simulate ram is to decrease the MHSIT. This is consistent with a decrease of the rate of chemical reactions at lower pressure as shown in the calculations presented in Section 5.1.2.

Furthermore, pressure can affect heat transfer; the effect, however, is:

(1) negligible for gas-phase heat transfer in sprays, and for film boiling in stream involving JP-4 and JP-8.

(2) significant for boiling in the nucleate regime, where increasing the pressure can activate nucleation sites at lower superheat temperature, thereby greatly enhancing boiling heat transfer rates. Such a boiling regime is believed to occur for sprays and streams of 83282 as found in Appendix E. (The boiling regime for 5606 and 7808 is somewhat intermediate between that of 83282 and that of JP-4 and JP-8. See Appendix E.)

These effects (items 1 and 2) are consistent with the data in Figures 44 and 45 where sprays and streams of 83282 show a much stronger pressure dependence than the other fluids in either spray or stream.

Effect of Ventilation Air Velocity, V_a

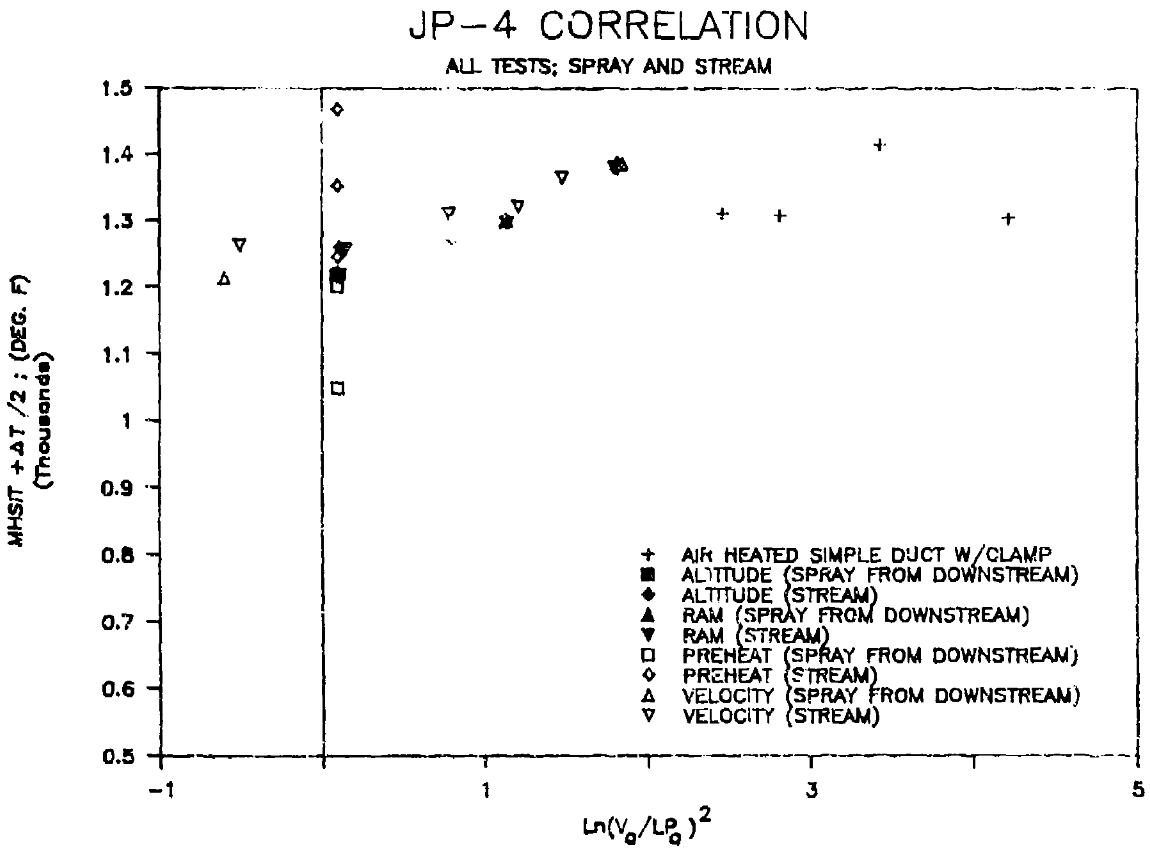
As shown in Figure 48 for 5606 and 83282, MHSIT increases with increasing V_a for both sprays and streams. This trend is consistent with the analysis in Section 5.1.2.

The difference between the results for the spray from upstream and downstream for 5606 is greater than expected. The spray from upstream data were acquired with an older nozzle, although of the same type as the rest of the data. The older nozzle may have been more worn, producing larger droplets. However, it is unclear whether the differences in these results can be attributed to the difference in the nozzles.

Data Correlation

The above discussions and the results of Section 5.1.2 suggest that the MHSIT temperature might be correlated with the ratio of ignition delay time to transit time, for both sprays and streams. This ratio depends on many variables as discussed in Appendix D and is difficult to determine particularly for the fluids for which we have no kinetic data. Alternatively, the parameter V_a/LP_a^2, which is an approximation for this ratio under the conditions of a kinetic-limited regime and a fixed chemistry (i.e., same fluid), was used. (Here L denotes a heating length and was taken to be the duct diameter for the simple duct data and the projected length of the hot duct along the ventilation air flow direction for the high realism tests).

The correlation between MHSIT and this parameter was tested and the results are shown in Figures 54 to 58 for each of the five fluids. Delta T, on the Y-axis, is the difference between the preheated air temperature and room temperature, 80°F. As noted in Section 5.1.2, the effect of air preheating can be approximated by increasing the duct temperature



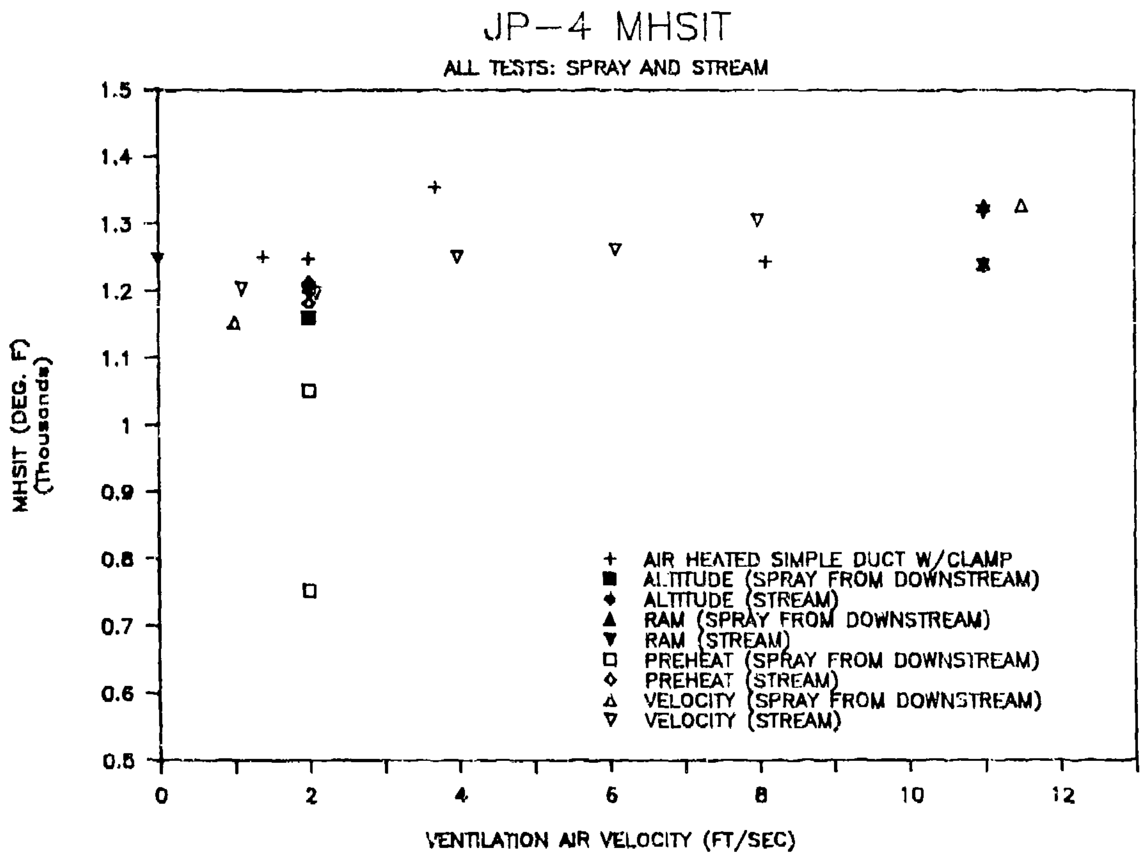
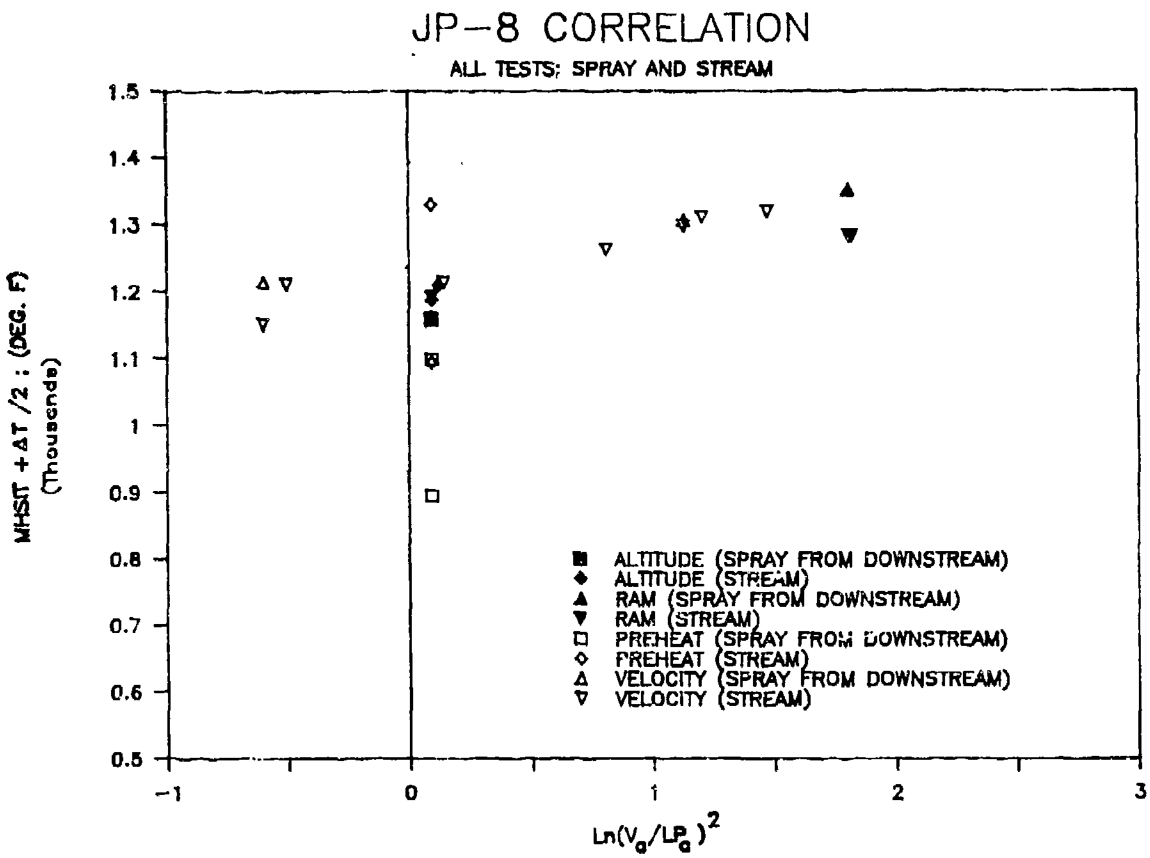


Figure 54. JP-4 Correlation Based on a Simplified Expression of Ignition Delay and Transit Time



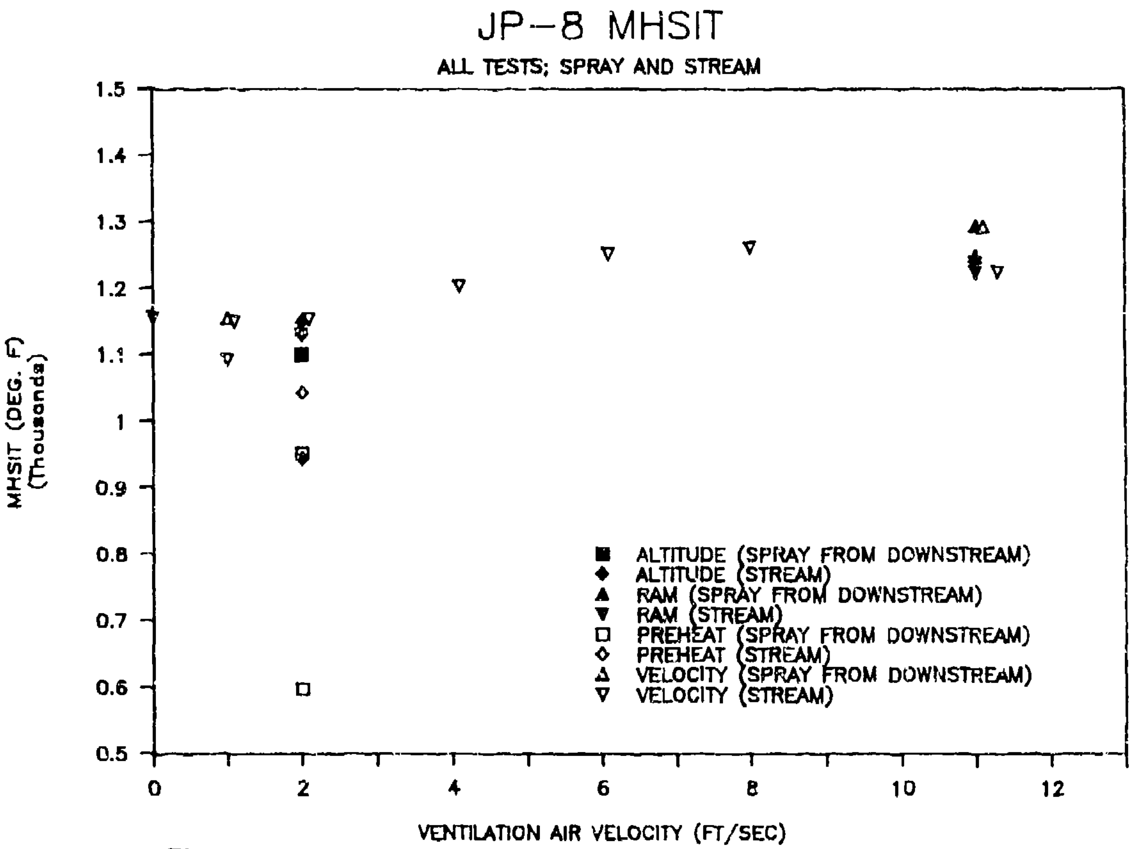


Figure 55. JP-8 Correlation Based on a Simplified Expression of Ignition Delay and Transit Time

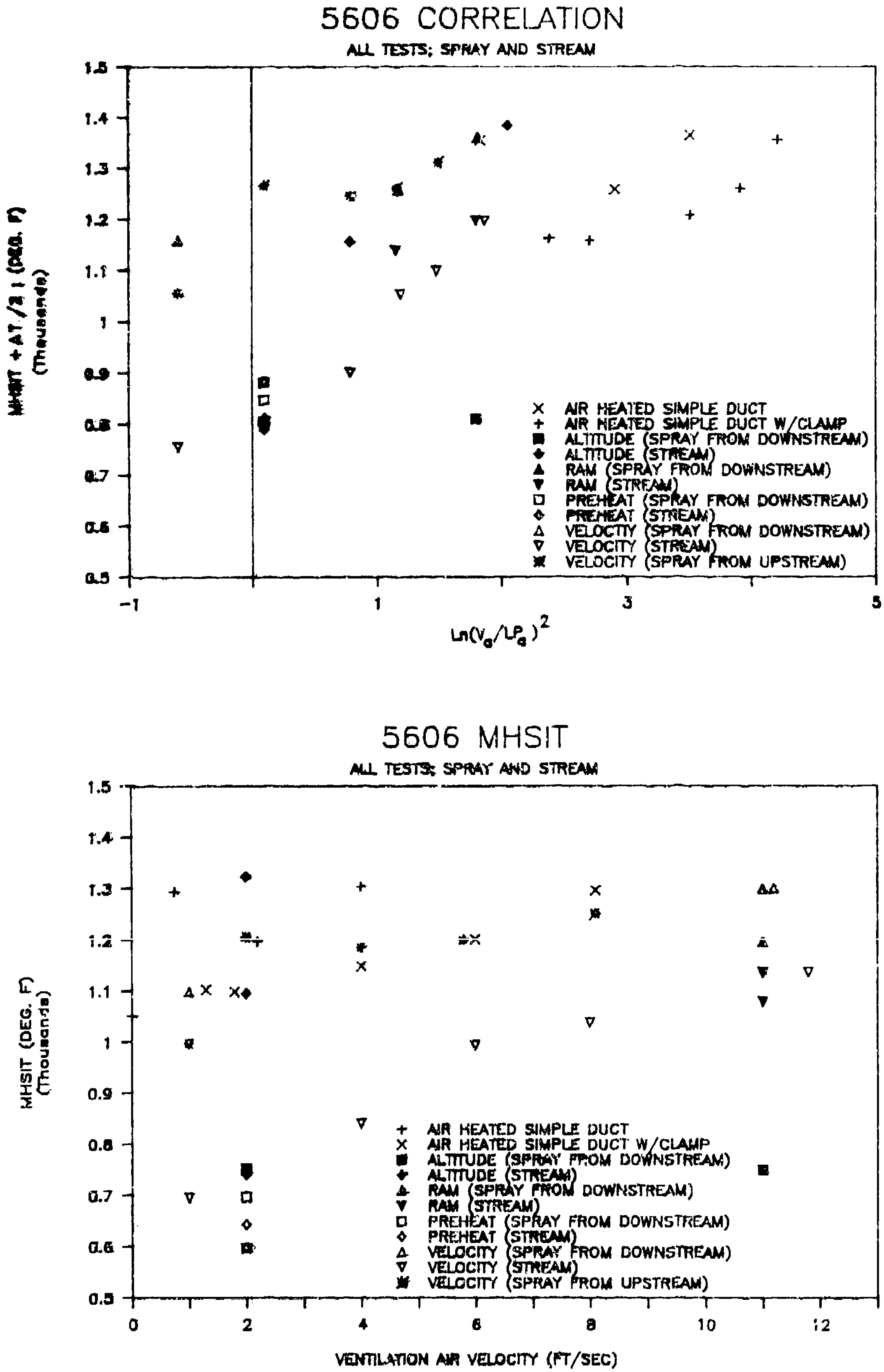
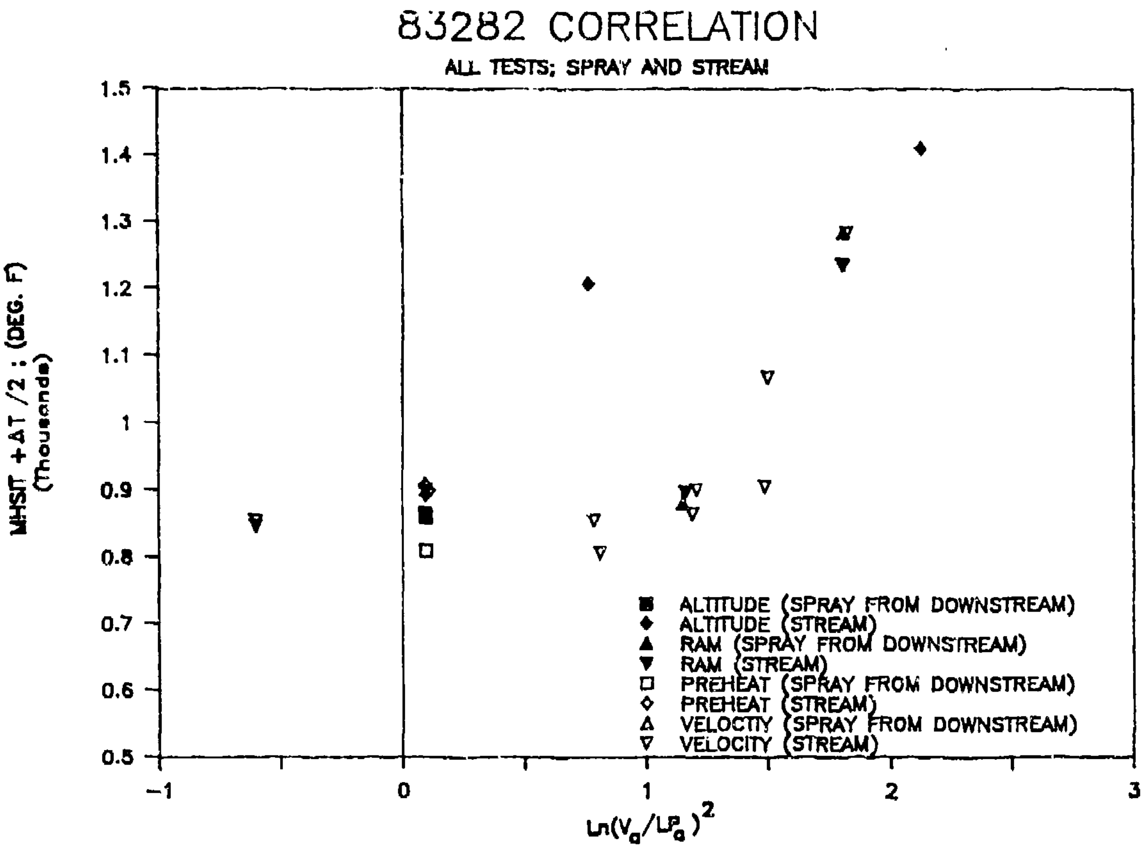


Figure 56. 5606 Correlation Based on a Simplified Expression of Ignition Delay and Transit Time



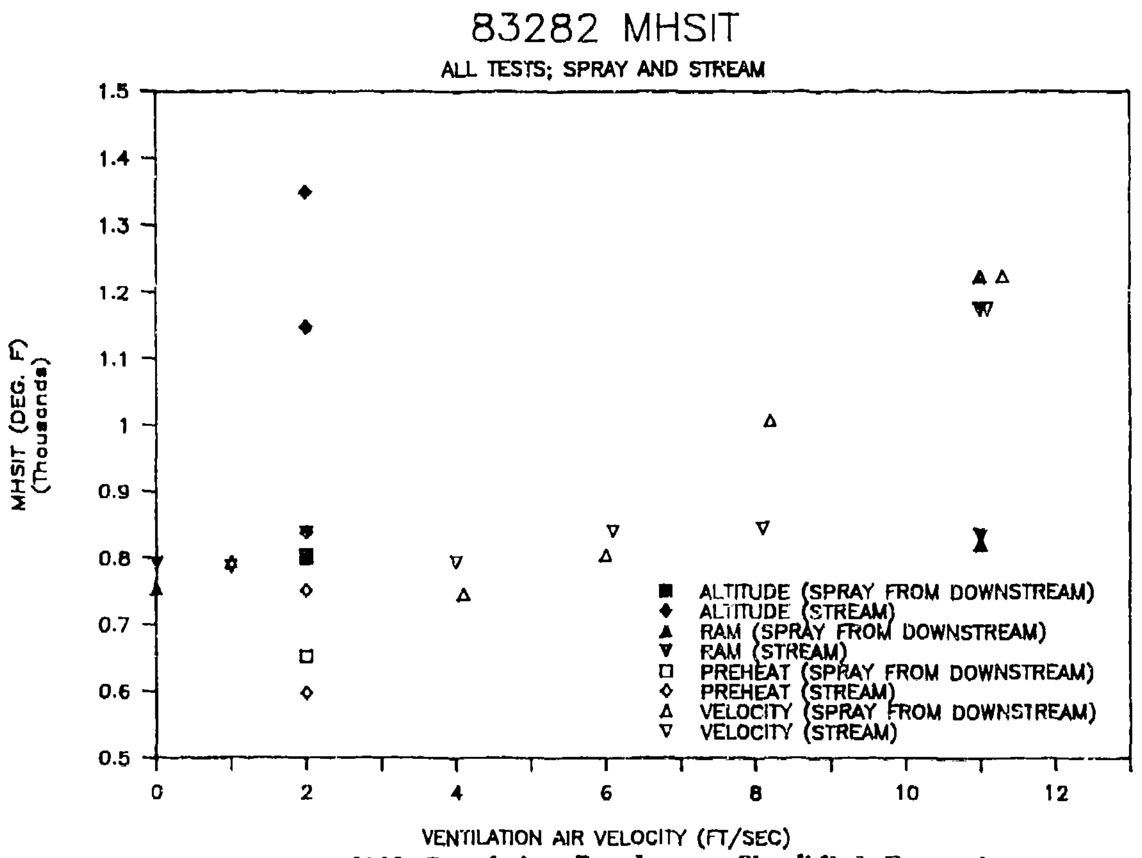
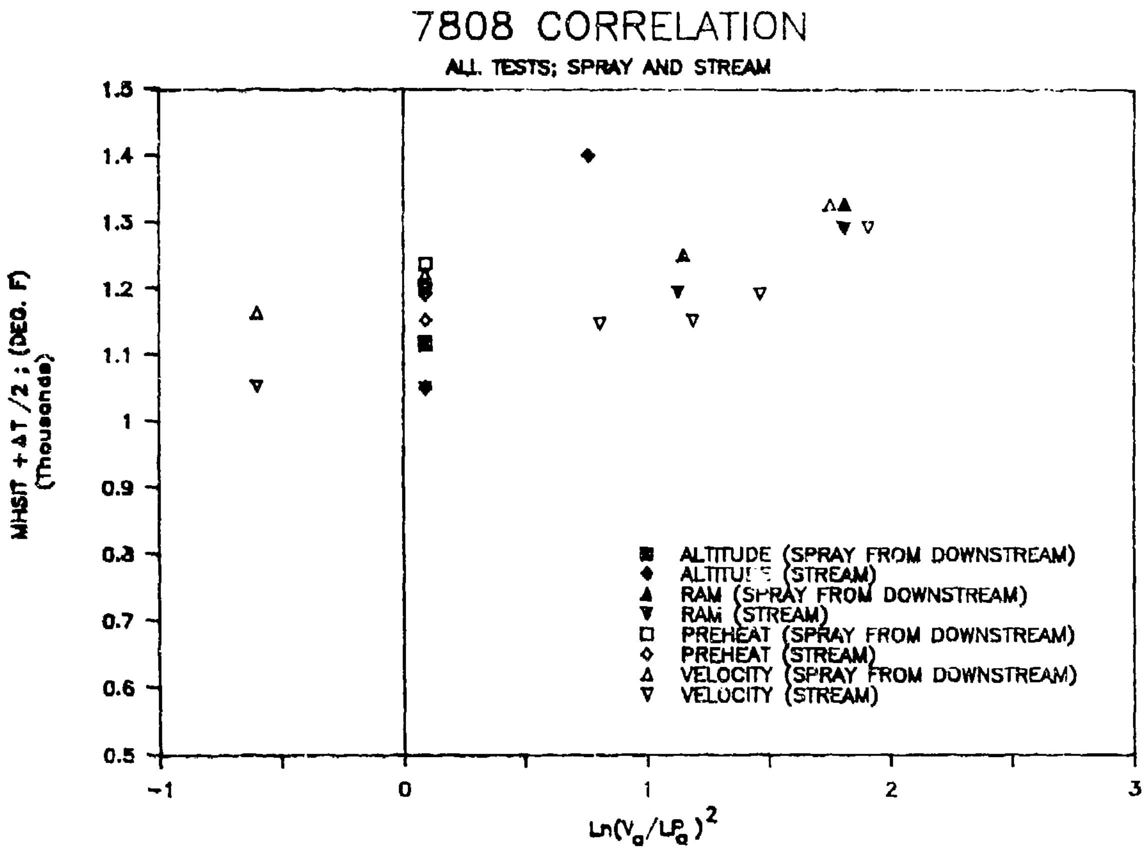


Figure 57. 83282 Correlation Based on a Simplified Expression of Ignition Delay and Transit Time



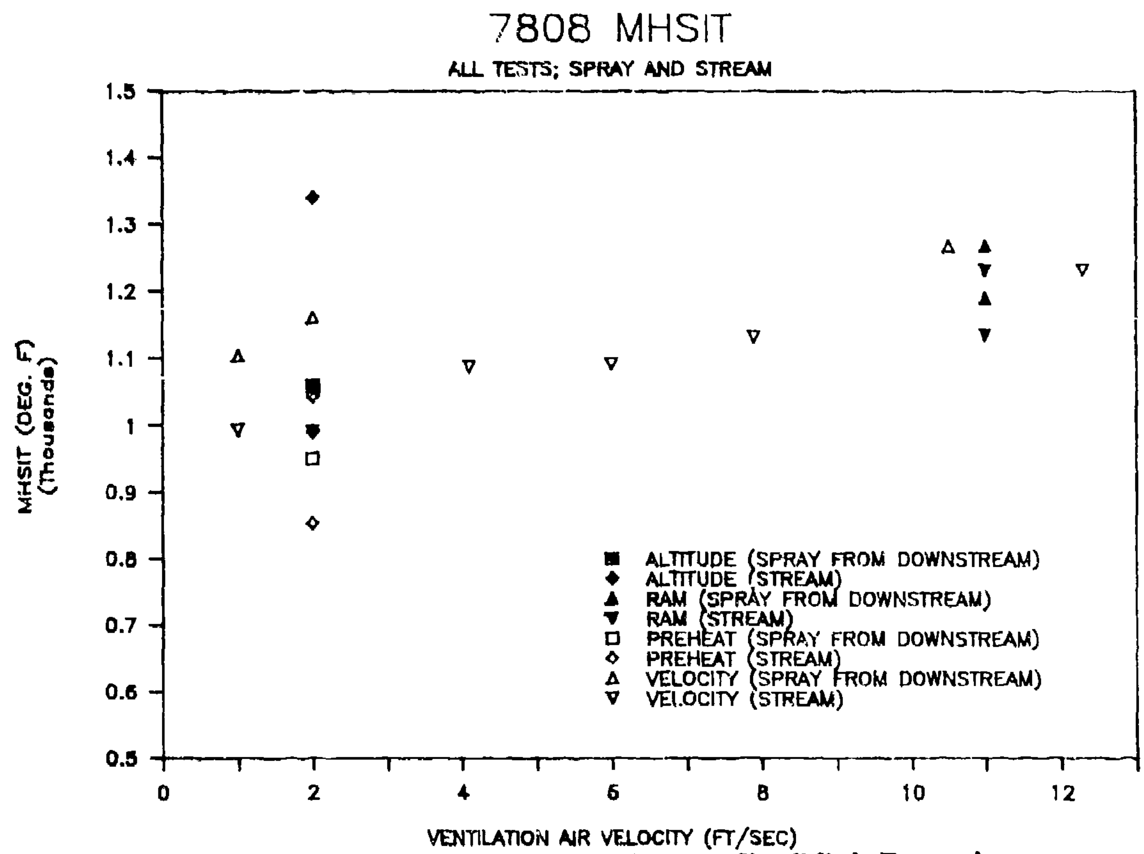


Figure 58. 7808 Correlation Based on a Simplified Expression of Ignition Delay and Transit Time

(reaction temperature) by half the preheat temperature. The top and bottom halves of each Figure include the same data shown with the proposed correlation at the top and MHSIT versus V_a at the bottom. This permits evaluation of the use of this correlation.

Despite the large scatter in all these plots, note that the correlation is superior to the use of MHSIT. Furthermore, the correlation can be considered particularly successful for 83282 (except for one data point) . The success of the correlation for 83282 fluid suggests that its ignition delay is mainly limited by chemical kinetics; while it is not for the other fluids, where other processes are also important. This finding is consistent with the low MHSITs found for 83282 and the inference that it boils in a nucleate regime. However, more work is required to determine with certainty the relationships between such findings.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The results of the present study add significantly to the data base available on hot surface ignition temperature, particularly as it applies to aircraft engine compartment design. The most important features of the new data are:

- their collection on a simulated portion of an F-16 nacelle using real components and systems

- a systematic variation of ventilation air pressure, temperature and velocity covering a range of realistic conditions simulating aircraft operation under various ram and altitude conditions

- use of the five flammable fluids of most interest in aircraft applications injected as sprays or streams and determination of their relative performance under identical test condition

- ignitions of 83282 at temperatures below its AIT per ASTM D 2155

Key findings of this study include:

The difference in MHSIT between sprays and streams is significant for JP-4 and JP-8 but less so for 5606, 7808 and 83282.

Generally, the MHSIT occurred above the autoignition temperature of the fluids except for the case of an 83282 (spray or stream) with preheated 600°F air, where ignition occurred at a temperature below the autoignition temperature of that fluid.

The results of this study were interpreted in light of simplified analyses of the key processes involved in hot surface ignition. These include chemical kinetics and droplet atomization, dynamics, heating and vaporization (for sprays) and regime of boiling heat transfer (nucleate versus film) for streams. Thus the observed differences and similarities between the various fluids and between sprays and streams were interpreted. Also a correlation is presented to describe the effects of the ventilation air test conditions on the MHSIT for each fluid.

The aircraft engine compartment designer should attempt to employ real data to establish safe design temperatures in new aircraft engine compartments. Extreme caution should be employed in any extrapolation of such data to untested conditions.

6.2 Recommendations

In retrospect, a number of recommendations about this test program can be made. Modifications of test method and instrumentation as well as new tests to be performed are suggested.

1. A test using the stream injection of the test fluids on the air heated simple duct should be performed. No data on the MHSIT for stream on the simple duct was taken in this test program. A fluid stream directly onto a thermocouple tack-welded onto the simple duct would provide temperature vs. time response of a wetted surface on the duct and this data would provide insight into the boiling regimes and heat transfer coefficients of the various test fluids. This data is important to allow correlation of hot surface ignition variables with MHSIT.

2. In the future, installation of a high speed motion picture camera to film the simple duct during injection and ignition would be a useful tool. This would provide information as to the exact location of ignition on the duct as well as the velocity of the flame front.

3. Absolutely scrupulous leak checking and leak repairing is a requirement for using air to heat a bleed air duct for hot surface ignition testing. Some simple duct data was called into question due to the existence of air leaks during the simple duct phase of the HSIT test program.

4. Since it was found that the local ventilation velocity was more important than the average ventilation velocity in the obstruction fill' high realism test article, it is desirable in the future to characteriz the ventilation velocities at the stream location sites. Measurement o. local ventilation air temperatures may also prove to be more meaningful than an upstream ventilation air temperature measurement.

5. In this test program, nitrogen was used to pressurize the fluid reservoirs in order to inject the fluid at the proper flowrate. However, as the fluid was streamed onto the duct, the observation was often made that gas would bubble out of the fluid. Assuming that this gas was nitrogen, it may have affected the local oxygen concentration, driving the MHSIT higher. To lessen this effect, and to better simulate the aircraft engine compartment (where fluids are generally pressurized by pumps) air would be a more suitable gas with which to pressurize the fluid reservoirs.

6. The effect of fluid temperature on MHSIT was not formally studied in this test program. In spite of the difficulties of measuring and controlling fluid temperature, it would be a worthwhile variable to study in the context of MHSIT.

7. Data concerning the effect of air pressure on the fluid AIT's was sought and not found. Additional testing directed at defining this effect might help to interpret MHSIT phenomena.

8. Additional research should be directed to interpret the finding that for 83282 (only) the MHSIT occurred at a temperature below the AIT.

9. The ignition delay time was measured during these tests and the results are reported in Appendix A. They should be analyzed in future work.

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APPENDIX A: SUMMARY OF HOT SURFACE IGNITION TEST DATA

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)

SIMPLE DUCT TEST ARTICLE
5606 SPRAY, HOT AIR HEATED BARE DUCT 8/26/87

0.91	133	14.13	1352	F	6.1
1.81	134	14.13	1351	F	6.3
4.00	126	14.13	1309	N	
3.93	124	14.13	1328	N	
4.00	124	14.13	1336	F	6.2
3.99	122	14.13	1305	F	6.4
6.00	130	14.12	1303	N	
6.06	130	14.12	1331	N	
8.06	130	14.12	1332	N	
8.02	129	14.12	1333	N	
8.02	128	14.12	1330	N	
6.28	129	14.12	1341	N	
6.22	128	14.12	1338	N	
1.91	127	14.12	1301	F	6.2
0.75	134	14.12	1295	F	6.1
0.89	142	14.12	1248	N	
0.99	144	14.12	1250	N	
0.70	147	14.12	1251	N	
1.96	137	14.12	1251	F	6.8
3.94	133	14.12	1249	N	
3.95	133	14.12	1253	N	
3.99	131	14.12	1252	N	
1.95	127	14.12	1205	N	
2.19	127	14.12	1198	F	7.6
1.88	128	14.12	1150	N	
1.75	127	14.12	1150	N	
2.00	127	14.12	1150	N	

SIMPLE DUCT TEST ARTICLE
JP-4 SPRAY, HOT AIR HEATED BARE DUCT 8/27/88

0.90	129	14.42	1333	N	
1.09	136	14.43	1337	N	
1.95	128	14.43	1358	N	
1.94	125	14.43	1359	N	
1.82	126	14.43	1363	N	
3.97	118	14.43	1370	N	
4.04	120	14.43	1368	N	
4.01	117	14.43	1366	N	
5.73	117	14.43	1370	N	
5.95	116	14.43	1374	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
6.01	117	14.43	1377	N	
8.04	117	14.43	1370	N	
8.07	118	14.43	1369	N	
8.11	117	14.43	1370	N	
1.68	124	14.43	1373	N	
1.36	143	14.43	1357	N	

SIMPLE DUCT TEST ARTICLE
JP-4 SPRAY, HOT AIR HEATED DUCT WITH CLAMP 8/28/87

1.12	134	14.25	1344	F	5.9
1.79	133	14.25	1363	F	5.9
3.68	127	14.28	1372	F	6.3
6.00	122	14.24	1364	N	
5.99	118	14.28	1369	N	
5.99	117	14.25	1372	N	
8.12	117	14.28	1373	N	
8.14	116	14.24	1376	F	6.9
1.15	126	14.28	1304	F	6.4
1.78	130	14.29	1305	F	6.2
4.05	124	14.29	1316	N	
4.04	124	14.28	1317	N	
4.02	124	14.23	1318	N	
8.12	118	14.29	1330	N	
8.17	119	14.28	1337	N	
8.11	118	14.28	1337	N	
1.36	126	14.28	1257	F	6.4
2.07	127	14.28	1254	N	
1.98	128	14.28	1255	F	6.4
1.10	138	14.28	1205	N	
1.12	139	14.26	1201	N	
1.29	144	14.26	1204	N	
1.94	133	14.28	1209	N	
2.05	130	14.28	1202	N	
1.82	130	14.28	1205	N	

SIMPLE DUCT TEST ARTICLE
5606 SPRAY, HOT AIR HEATED DUCT WITH CLAMP 8/31/87

1.27	142	14.21	1287	F	6.1
1.91	127	14.21	1301	F	6.3
4.01	114	14.21	1316	F	6.2
5.95	112	14.21	1323	F	6.5
8.10	112	14.21	1330	F	18.9
1.31	131	14.20	1243	F	6.3

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.96	129	14.20	1255	F	6.3
4.05	122	14.20	1266	F	6.2
5.98	116	14.20	1274	F	13.1
8.03	116	14.20	1301	N	
8.06	116	14.20	1303	N	
8.07	115	14.20	1307	N	
1.28	129	14.20	1205	F	6.4
1.87	132	14.20	1207	F	6.4
4.05	126	14.20	1217	F	6.4
5.91	121	14.20	1227	N	
5.96	121	14.20	1250	F	7.5
1.13	128	14.20	1155	N	
1.43	134	14.20	1165	F	6.4
2.05	135	14.20	1160	F	6.5
4.00	128	14.20	1173	F	6.8
5.97	124	14.20	1182	N	
6.00	122	14.20	1198	N	
5.97	121	14.20	1198	N	
1.15	131	14.20	1103	N	
1.29	133	14.20	1110	F	25.3
1.97	134	14.20	1111	F	6.6
3.96	129	14.20	1122	F	6.6
1.24	135	14.20	1048	F	7.4
2.12	135	14.20	1064	F	7.4
1.30	134	14.20	1085	F	6.8
1.77	128	14.19	1103	F	7.2
3.91	125	14.19	1131	N	
4.17	122	14.19	1120	N	
4.05	119	14.20	1123	N	
4.01	113	14.18	1156	F	6.5
1.37	125	14.17	1041	N	
1.24	128	14.14	1056	N	
1.23	131	14.12	1052	N	
1.94	122	14.18	1060	N	
1.99	120	14.18	1057	N	
2.00	117	14.18	1063	N	

SIMPLE DUCT TEST ARTICLE
5606 SPRAY, HOT AIR HEATED DUCT WITH CLAMP (VERTICAL) 9/9/87

1.34	119	14.37	1318	N	
1.08	123	14.37	1352	N	
0.98	122	14.37	1351	N	
1.28	124	14.37	1352	N	
1.90	125	14.37	1357	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.96	124	14.37	1360	N	
1.97	125	14.37	1353	N	
3.69	123	14.37	1356	N	
3.94	122	14.37	1352	N	
4.03	121	14.37	1353	N	
5.89	120	14.37	1346	N	
5.97	120	14.37	1350	N	
5.96	119	14.37	1349	N	
8.01	119	14.37	1345	N	
8.04	118	14.36	1343	N	
8.09	118	14.36	1347	N	

SIMPLE DUCT TEST ARTICLE
5606 SPRAY, RESISTANCE HEATED BARE DUCT 9/15/87

1.13	92	14.39	1169	N	
1.25	98	14.38	1235	N	
0.99	101	14.40	1308	F	8.1
1.07	103	14.40	1251	F	6.2
1.19	111	14.40	1200	N	
1.00	115	14.40	1201	F	6.7
1.27	120	14.40	1155	F	7.8
1.18	120	14.39	1100	N	
1.26	118	14.39	1096	N	
0.93	117	14.39	1105	N	
2.02	115	14.39	1120	N	
2.00	113	14.39	1121	N	
1.83	112	14.39	1123	N	
2.04	111	14.39	1176	N	
1.90	111	14.39	1181	N	
1.92	111	14.39	1174	N	
1.81	112	14.39	1230	F	7.4
1.97	114	14.39	1179	N	
2.11	112	14.39	1172	F	7.4
1.86	112	14.40	1127	N	
1.95	111	14.39	1123	N	
1.89	111	14.39	1125	N	
3.96	114	14.39	1411	N	
3.94	116	14.39	1455	F	5.9
4.02	116	14.39	1418	F	7.6
3.99	117	14.39	1362	F	6.6
4.04	117	14.39	1316	N	
3.97	117	14.39	1312	N	
4.05	117	14.39	1313	N	
6.00	118	14.39	1506	F	6.8

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
6.05	120	14.39	1472	N	
6.06	120	14.39	1472	N	
6.08	120	14.40	1471	N	
8.08	120	14.41	1544	F	6.4
8.09	120	14.41	1493	N	
8.11	120	14.41	1489	N	
8.07	119	14.41	1488	N	

SIMPLE DUCT TEST ARTICLE
JP-4 SPRAY, RESISTANCE HEATED SIMPLE DUCT 9/15/87

8.08	116	14.34	1533	N	
8.09	117	14.34	1559	N	
8.10	117	14.34	1544	F	6.4
8.14	119	14.33	1488	N	
8.08	120	14.32	1484	N	
8.12	120	14.32	1488	N	
6.18	121	14.31	1522	N	
6.20	122	14.31	1523	F	6.2
6.10	123	14.34	1474	N	
6.09	121	14.34	1467	N	
6.05	122	14.34	1470	N	
4.02	123	14.34	1496	F	6.4
4.11	124	14.34	1454	N	
4.03	124	14.34	1448	N	
4.08	124	14.34	1449	N	
2.03	125	14.34	1474	F	
2.22	127	14.34	1424	N	
1.99	127	14.34	1424	F	6.2
2.15	127	14.34	1381	N	
2.20	127	14.34	1379	F	6.6
2.16	125	14.34	1332	N	
2.15	124	14.33	1333	N	
2.22	123	14.32	1333	N	
1.22	127	14.33	1412	F	6.2
0.85	133	14.32	1367	N	
1.01	132	14.32	1371	F	6.4
1.02	133	14.32	1329	N	
1.29	132	14.32	1326	N	
1.16	130	14.32	1323	N	

SIMPLE DUCT TEST ARTICLE
5606 SPRAY, RESISTANCE HEATED DUCT WITH CLAMP 9/17/87

8.12	113	14.21	1487	F	6.4

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
8.08	113	14.21	1435	F	6.2
8.14	113	14.23	1385	N	
8.12	114	14.20	1386	F	7.3
8.11	114	14.25	1336	N	
8.13	115	14.20	1334	N	
8.13	115	14.25	1335	N	
6.15	116	14.23	1473	F	6.5
6.12	116	14.24	1420	F	6.1
6.08	117	14.24	1368	F	6.9
6.06	116	14.25	1319	F	6.7
6.01	116	14.25	1272	N	
5.99	116	14.23	1269	N	
6.02	117	14.25	1270	N	
4.07	117	14.24	1353	F	6.4
4.09	118	14.23	1307	F	6.4
4.12	117	14.19	1254	F	9.6
4.05	118	14.22	1203	N	
4.05	117	14.24	1203	F	10.5
4.10	117	14.25	1159	N	
4.07	117	14.23	1151	N	
4.05	118	14.21	1153	N	
2.14	118	14.20	1223	F	8.3
2.11	117	14.24	1176	F	10.4
2.12	117	14.20	1128	N	
2.20	117	14.21	1123	N	
2.10	117	14.13	1122	N	
0.89	118	14.10	1205	F	6.7
1.16	117	14.15	1158	N	
1.07	117	14.17	1156	N	
1.27	116	14.10	1158	F	7.7
1.18	117	14.14	1110	N	
1.14	115	14.17	1106	N	
1.28	116	14.18	1106	N	

SIMPLE DUCT TEST ARTICLE
JP-4 SPRAY, RESISTANCE HEATED DUCT WITH CLAMP 9/18/87

8.14	106	14.14	1536	F	6.3
8.12	108	14.06	1488	N	
8.11	108	14.09	1483	N	
8.15	108	14.02	1486	N	
6.07	110	14.10	1521	N	
6.04	110	14.08	1522	F	6.2
6.08	110	14.11	1471	N	
6.06	111	14.11	1468	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
6.02	111	14.03	1467	N	
4.13	112	14.08	1506	F	6.3
4.04	112	14.15	1453	N	
4.02	113	14.18	1449	N	
4.03	113	14.18	1449	N	
2.06	115	14.19	1425	N	
2.07	115	14.18	1426	F	6.4
1.92	115	14.18	1374	N	
2.07	116	14.17	1372	N	
2.06	114	14.18	1375	N	
0.98	116	14.19	1407	F	5.9
0.88	118	14.18	1360	F	6.7
1.24	119	14.18	1309	N	
1.14	117	14.19	1306	N	
1.33	117	14.18	1306	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE 5606, SPRAY FROM UPSTREAM			11/17/87		
1.08	100	14.29	1364	F	1.3
2.06	127	14.29	1295	F	1.8
4.14	117	14.29	1279	F	1.7
6.17	103	14.29	1299	F	6.2
7.90	126	14.29	1336	F	2.3
1.07	133	14.29	1249	F	2.5
1.95	133	14.28	1207	F	2.5
4.03	129	14.28	1215	F	4.5
6.04	122	14.28	1200	N	
5.88	119	14.28	1249	N	
5.95	113	14.29	1302	F	4
7.85	112	14.28	1302	F	5
8.11	113	14.29	1256	N	
8.07	125	14.29	1252	F	5.3
5.94	131	14.29	1252	F	0.8
6.00	119	14.28	1265	F	6.6
1.07	131	14.28	1157	F	5.9
1.93	136	14.28	1160	N	
1.90	138	14.28	1156	N	
1.88	143	14.28	1156	N	
4.07	159	14.28	1172	N	
3.94	159	14.28	1185	F	5.3
3.95	162	14.28	1163	N	
3.89	162	14.28	1157	N	
3.89	161	14.28	1154	N	
5.63	155	14.28	1212	F	2.7
5.65	146	14.28	1169	N	
5.51	144	14.28	1165	N	
6.04	137	14.28	1162	N	
8.03	123	14.28	1216	N	
7.66	118	14.28	1223	N	
7.61	119	14.28	1212	N	
HIGH REALISM TEST ARTICLE 5606, SPRAY FROM UPSTREAM			11/18/87		
1.04	93	14.47	1247	F	3.3
1.03	97	14.47	1201	F	6.1
1.23	215	14.47	1158	F	4.7
1.04	118	14.47	1090	N	
1.03	118	14.47	1096	N	
1.00	121	14.47	1101	F	5.7

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
0.98	123	14.47	1056	F	5.1
0.97	130	14.47	1004	N	
0.96	134	14.47	996	N	
0.95	126	14.47	1001	N	
1.00	136	14.47	1099	F	4.4
1.02	147	14.47	1105	F	5.7
5.80	117	14.47	1252	F	5.7
5.85	119	14.48	1201	F	6.2
5.91	117	14.48	1153	N	
5.80	113	14.48	1150	N	
6.09	111	14.48	1151	N	
20fps, all no fire					
0.00	125	14.48	1335	N	
0.00	113	14.47	1363	N	
0.00	117	14.47	1373	N	
4ml/sec spray flowrate					
1.00	157	14.48	1199	F	3.1
1.01	131	14.48	1150	N	
1.00	143	14.48	1147	F	2.6
1.01	131	14.48	1102	N	
1.01	140	14.48	1098	N	
1.01	147	14.48	1097	N	

HIGH REALISM TEST ARTICLE
5606 SPRAY FROM UPSTREAM, 4ml/sec, 11/19/87

1.94	122	14.50	1251	F	2.5
1.91	123	14.49	1199	F	2.3
1.93	124	14.50	1154	N	
2.03	124	14.49	1149	N	
1.96	123	14.50	1151	N	
4.03	131	14.49	1249	F	1.9
3.98	130	14.50	1205	N	
3.97	128	14.49	1198	F	4
3.99	125	14.49	1154	N	
3.85	123	14.49	1149	N	
3.95	122	14.49	1150	N	
5.94	113	14.49	1256	N	
5.99	136	14.49	1345	F	1.2
6.06	136	14.49	1305	F	1.7
5.94	134	14.49	1251	F	2.2
5.98	132	14.48	1205	N	
5.95	131	14.48	1200	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
5.83	128	14.48	1199	N	
7.97	120	14.48	1294	F	7.5
7.76	118	14.48	1247	N	
7.92	119	14.48	1248	N	
7.93	122	14.48	1251	N	
0.00	148	14.46	1245	F	2.6
0.00	165	14.46	1203	F	3.1
0.00	147	14.45	1148	F	6.1
0.00	143	14.45	1102	N	
0.00	147	14.45	1096	N	
0.00	118	14.45	1097	N	
0.93	117	14.45	1249	F	1.4
1.00	110	14.45	1203	F	1.6
1.00	104	14.45	1154	F	1.4
1.00	105	14.44	1105	N	
1.01	116	14.45	1099	N	
0.99	122	14.45	1097	N	
1.02	136	14.45	1247	F	2.9
0.91	107	14.44	1201	F	3.1
1.01	124	14.44	1153	F	4.8
0.99	118	14.44	1101	F	3.5
1.00	110	14.44	1050	F	4.4
0.99	108	14.44	1007	N	
1.02	115	14.44	996	N	
1.00	118	14.44	997	F	3.1
0.99	110	14.44	958	N	
1.00	114	14.44	949	N	
1.00	117	14.44	949	N	

HIGH REALISM TEST ARTICLE
5606, SPRAY FROM UPSTREAM, 300 PNZFUL, 11/20/87

0.00	131	14.35	1193	N	
0.00	131	14.35	1241	F	2
0.00	128	14.34	1206	F	3.3
0.00	131	14.33	1153	F	5
0.00	125	14.33	1103	F	4.7
0.00	131	14.32	1052	N	
0.00	114	14.32	1053	F	4.9
0.00	131	14.33	1003	N	
0.00	98	14.35	999	N	
0.00	113	14.36	997	N	
7.63	130	14.35	1302	N	
7.82	124	14.35	1353	F	2.1
7.62	116	14.35	1296	F	5.7

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
7.66	110	14.35	1250	N	
8.00	113	14.35	1248	N	
7.91	114	14.34	1246	N	
4.01	122	14.36	1248	F	4.4
3.91	114	14.36	1204	N	
3.94	115	14.37	1198	N	
4.38	115	14.37	1198	N	
1.09	127	14.37	1249	F	2.3
1.10	146	14.38	1197	F	4.8
1.02	115	14.37	1153	N	
0.98	110	14.38	1149	F	7.5
1.01	123	14.38	1102	F	5.7
1.00	128	14.37	1053	N	
0.99	117	14.38	1047	N	
0.99	115	14.37	1050	F	5.9
1.04	123	14.37	1004	N	
1.00	109	14.37	999	N	
0.96	107	14.37	1000	N	

HIGH REALISM TEST ARTICLE
5606 DRIP, LOCATIONS 1 AND 2, 1/20/88
LOCATION 1, 11.8 SECOND INJECTION

1.09	144	14.17	1079	F	1.9
1.12	182	14.17	1130	F	1.6
1.09	169	14.16	1102	F	1.9
1.02	136	14.15	1034	F	15.4
1.00	140	14.15	1024	F	15.2
1.00	123	14.14	954	F	16
1.02	103	14.14	924	N	
1.01	114	14.14	932	N	
1.01	120	14.13	939	N	
7.90	109	14.13	1031	F	1.8
7.97	115	14.13	1043	F	15.4
8.04	119	14.13	1007	N	
7.85	122	14.13	961	N	
7.93	122	14.13	1009	N	

LOCATION 2,

1.01	134	14.13	1256	F	1.2
1.01	144	14.13	1205	F	3.7
1.01	127	14.12	1167	F	1.7
1.00	142	14.13	1082	F	1.6
1.00	122	14.13	1063	F	1.8

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.02	147	14.13	1029	F	1.6
0.99	127	14.13	983	F	1.7
1.02	117	14.13	938	F	2
0.99	110	14.13	855	N	
1.00	129	14.13	879	N	
0.98	134	14.13	885	N	

HIGH REALISM TEST ARTICLE
5606 DRIP, LOCATIONS 2 AND 3, 1/21/88
location 2,

8.15	116	14.36	1199	F	2.1
7.85	120	14.35	1134	N	
7.92	120	14.35	1140	N	
7.97	120	14.36	1129	N	
7.98	117	14.34	1190	F	4.9

location 3, 11.1 sec injection

1.06	165	14.33	1187	F	1.5
1.01	150	14.33	1136	F	2.4
0.97	132	14.33	1088	F	2.4
0.99	139	14.33	1046	F	2.2
1.00	134	14.33	998	F	2.2
0.98	129	14.33	948	F	3.6
1.00	121	14.33	898	F	2.6
1.00	122	14.33	847	F	2.6
1.01	112	14.33	799	F	2.9
0.99	93	14.33	743	F	2.9
0.99	97	14.33	699	N	
0.99	108	14.33	697	F	7.4
1.01	111	14.33	645	N	
1.02	112	14.33	646	N	
1.02	109	14.32	647	N	
1.00	111	14.32	702	N	
1.00	116	14.32	749	F	4.2
1.00	121	14.32	698	N	
0.99	122	14.32	696	N	
1.02	118	14.32	699	N	

HIGH REALISM TEST ARTICLE
5606 STREAM, LOCATION 3, 1/22/88

8.02	128	14.36	996	N	
7.88	130	14.36	1091	F	5.1

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
7.95	124	14.36	1040	N	
7.87	121	14.36	1039	N	
7.97	120	14.36	1039	F	9.4
7.75	117	14.36	994	N	
7.96	114	14.36	991	N	
7.64	112	14.36	993	N	

HIGH REALISM TEST ARTICLE
5606 STREAM, LOCATION 4 AND 5, 1/26/88
location 4

1.14	151	14.43	1152	N	
0.97	182	14.44	1248	F	3.7
0.72	200	14.44	1193	F	4.7
1.07	166	14.43	1151	F	15
1.02	154	14.43	1101	F	10.5
1.03	150	14.42	1053	F	13
1.00	153	14.42	1002	N	
1.02	172	14.42	1002	F	4.5
0.94	145	14.42	951	N	
0.98	159	14.42	951	N	
0.99	169	14.43	949	N	
7.77	128	14.42	1241	N	
8.13	144	14.42	1288	F	3.4
7.86	150	14.42	1240	N	
8.04	126	14.42	1234	N	
8.06	125	14.42	1237	N	
8.09	117	14.42	1286	F	2.9

location 5, straight on clamp

1.02	142	14.42	1240	F	2
1.03	167	14.43	1188	F	1.9
1.02	172	14.43	1146	F	2.1
0.99	146	14.43	1090	F	2.1
1.00	130	14.43	1042	F	2.6
0.99	119	14.42	993	F	2.6
0.99	108	14.43	930	F	3.3
0.96	109	14.43	890	F	4.6
0.94	89	14.43	841	N	
0.98	93	14.43	838	F	4.6
1.00	71	14.43	794	N	
0.99	88	14.43	792	N	
0.98	92	14.44	796	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE					
5606 STREAM, LOCATION 5 AND 6, 1/27/88					
loc 5 straight on clamp					
8.05	92	14.59	1180	F	5.6
8.12	94	14.59	1129	N	
7.95	95	14.59	1129	N	
8.03	103	14.58	1129	F	7.8
8.08	116	14.58	1081	N	
8.07	126	14.58	1081	F	6.7
7.86	133	14.58	1031	N	
7.91	131	14.58	1031	N	
7.98	127	14.58	1033	N	
location 6, drip 5606, 2ml/sec					
0.97	131	14.58	1298	F	3
0.98	138	14.58	1254	F	3.8
0.97	114	14.58	1214	N	
1.03	137	14.58	1207	N	
1.03	147	14.58	1207	F	8.7
0.99	109	14.58	1166	N	
1.00	130	14.57	1166	N	
1.01	144	14.57	1166	N	
8.05	117	14.57	1286	F	6.1
7.89	126	14.57	1230	F	3.6
7.80	127	14.57	1189	F	4.5
7.58	125	14.57	1146	N	
7.18	120	14.57	1144	N	
6.83	117	14.57	1143	N	
HIGH REALISM TEST ARTICLE					
5606 STREAM, LOCATION 3, 1/28/88					
0.98	101	14.62	1085	F	3.6
0.99	128	14.62	1036	F	2.6
1.00	117	14.62	988	F	3.9
1.00	114	14.62	935	F	6.3
0.99	115	14.61	887	F	8.6
0.99	115	14.61	838	F	6.3
0.99	117	14.61	788	F	9.3
1.00	119	14.61	738	N	
0.99	118	14.61	738	F	6.9
1.00	120	14.60	691	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.00	118	14.60	689	N	
0.98	115	14.60	688	N	
1.00	117	14.61	688	N	
1.00	117	14.60	689	N	
1.01	118	14.59	741	N	

HIGH REALISM TEST ARTICLE
5606 STREAM, LOCATION 3, 1/29/88
2ml/sec, 40sec

1.05	112	14.51	988	F	3.9
1.01	114	14.51	932	F	4.4
1.02	127	14.52	885	N	
1.01	131	14.51	936	F	3.7
0.99	135	14.51	886	F	4.3
0.99	136	14.51	838	F	5.2
1.00	143	14.51	792	N	
0.98	146	14.51	842	F	9.7
0.99	144	14.51	792	N	
0.99	141	14.51	788	N	
1.00	137	14.51	787	F	4.1
1.00	132	14.51	741	N	
0.99	128	14.50	739	F	10.3
1.00	133	14.50	694	N	
1.00	129	14.50	693	N	
1.01	128	14.50	693	N	

4ml/sec, 40sec

1.02	151	14.50	843	F	39
1.01	142	14.49	789	N	
1.00	143	14.50	791	N	
1.00	129	14.49	791	F	41.8
1.00	152	14.49	739	N	
0.99	131	14.49	739	N	
1.02	126	14.49	739	N	

1ml/sec, 40 sec

1.00	98	14.48	845	N	
1.01	112	14.48	892	F	4.7
1.00	114	14.48	833	N	
1.02	116	14.48	830	N	
1.02	116	14.48	834	F	3.8

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE 5606 STREAM, LOCATION 3 AND 5, 2/1/88 location 3					
3ML/SEC					
1.02	110	14.39	987	F	3
1.01	126	14.39	917	F	3.2
1.00	129	14.39	886	N	
0.99	132	14.38	886	F	2.7
1.00	131	14.38	835	F	2.7
1.00	127	14.38	786	F	3.7
1.00	124	14.38	734	N	
0.99	119	14.38	734	N	
1.01	119	14.37	735	N	
2ML/SEC					
1.01	116	14.37	787	N	
1.00	122	14.37	840	F	2.6
0.99	124	14.3,	784	N	
1.00	121	14.37	782	F	5.4
1.02	120	14.37	734	N	
0.99	118	14.37	731	N	
1.00	115	14.37	736	N	
1ML/SEC					
1.01	123	14.37	845	F	4.9
1.01	130	14.37	787	N	
1.02	127	14.37	785	N	
1.00	126	14.37	786	F	4
1.00	126	14.37	734	N	
1.02	124	14.37	736	N	
1.01	122	14.37	737	N	
HIGH REALISM TEST ARTICLE 5606 drip, location 5, oblique onto clamp, 2 ml/sec					
1.02	124	14.36	901	N	
1.00	125	14.37	953	N	
1.02	125	14.36	1001	N	
1.03	146	14.37	1196	F	1.6

HIGH REALISM TEST ARTICLE
5606 STREAM, LOCATION 5 AND 3, 2/2/88

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
location 5		oblique on clamp			
1.00	147	14.50	1142	F	2.2
1.06	161	14.51	1087	F	2
0.98	137	14.51	1039	N	
1.01	154	14.50	1042	F	2.5
0.98	126	14.50	995	N	
1.00	134	14.50	996	N	
1.00	143	14.50	996	F	4.9
0.99	132	14.50	944	N	
1.00	131	14.50	945	N	
1.00	131	14.50	946	N	
location 3					
5.85	113	14.49	1092	F	2.4
6.00	114	14.50	1045	F	3.2
5.97	112	14.49	995	F	3.6
5.92	110	14.49	942	N	
6.05	112	14.49	942	N	
6.01	113	14.49	944	N	
4.10	115	14.49	946	F	12.1
4.03	113	14.49	897	F	2.6
3.91	112	14.49	843	N	
3.97	112	14.49	841	F	4.7
4.00	109	14.49	796	N	
3.98	112	14.49	795	N	
4.05	113	14.49	793	N	
2.01	117	14.49	852	F	2.8
2.00	121	14.50	793	N	
2.02	119	14.49	786	F	3.2
2.01	119	14.49	743	N	
2.00	118	14.50	741	N	
2.02	117	14.50	741	F	7
1.99	112	14.50	690	N	
2.01	114	14.50	685	N	
2.00	113	14.50	695	N	

HIGH REALISM TEST ARTICLE
5606 SPRAY FROM DOWNSTREAM, 2/3/88

1.00	112	14.45	1057	N	
1.00	119	14.45	1100	F	5.8
1.00	138	14.45	1055	N	
1.00	135	14.44	1053	N	
0.99	135	14.44	1053	N	
0.99	136	14.44	1099	F	5.9

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
8.24	102	14.43	1152	N	
7.96	126	14.42	1199	N	
7.87	125	14.41	1256	F	5.8
7.84	124	14.41	1206	N	
8.06	124	14.41	1204	F	5.8
7.95	121	14.41	1158	N	
7.88	119	14.41	1154	N	
7.91	117	14.41	1153	F	6.3
7.98	113	14.41	1106	F	6.2
8.02	118	14.40	1047	N	
7.92	113	14.41	1049	N	
7.91	113	14.41	1051	N	

HIGH REALISM TEST ARTICLE
JP-4 SPRAY FROM DOWNSTREAM, 2/3/88

7.98	112	14.40	1253	N	
7.90	109	14.40	1281	N	
8.05	109	14.40	1281	F	6
7.97	106	14.40	1207	N	
8.00	80	14.40	1211	N	
8.01	80	14.40	1211	N	
7.92	79	14.39	1213	N	
1.17	133	14.40	1202	N	
1.05	140	14.40	1249	F	5.7
1.00	125	14.39	1207	F	5.7
1.00	124	14.39	1157	N	
1.01	136	14.39	1154	F	6.5
0.96	115	14.39	1105	N	
1.00	122	14.39	1100	N	
1.00	129	14.39	1099	N	

HIGH REALISM TEST ARTICLE
JP-4 SPRAY FROM UPSTREAM, 2/4/88

1.08	177	14.48	1354	F	1.3
1.03	171	14.49	1306	F	1.5
0.95	122	14.48	1251	F	2.2
0.97	134	14.48	1205	F	5.9
0.95	120	14.48	1153	N	
0.99	135	14.48	1148	N	
1.00	150	14.48	1147	N	
8.03	97	14.48	1301	N	
8.03	108	14.48	1359	F	1.3
8.00	110	14.48	1306	F	1.7

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
7.84	113	14.48	1256	N	
8.07	113	14.47	1247	N	
7.92	112	14.47	1248	N	

HIGH REALISM TEST ARTICLE
JP-4 STREAM, LOCATION 1,2,3,4 , 2/5/88

LOCATION 1					
1.05	163	14.56	1130	F	2.7
1.01	144	14.56	1073	N	
0.98	132	14.56	1069	N	
0.98	127	14.56	1068	F	8.2
1.02	145	14.56	1042	N	
0.98	122	14.55	1021	N	
0.98	124	14.54	1015	N	
LOCATION 2					
1.03	146	14.54	1213	F	2.7
1.02	140	14.54	1163	F	3.5
1.00	136	14.54	1112	F	6.3
1.00	125	14.54	1071	N	
0.98	104	14.54	1070	N	
1.01	107	14.54	1072	N	
LOCATION 3					
0.99	101	14.54	1088	N	
1.02	128	14.54	1140	N	
1.03	128	14.54	1187	F	18.7
1.01	111	14.54	1138	N	
1.03	133	14.53	1139	N	
1.01	109	14.53	1136	N	
1.05	128	14.53	1191	F	12.1
LOCATION 4					
1.00	108	14.54	1237	F	9.6
1.00	111	14.54	1183	N	
1.01	132	14.54	1187	N	
1.00	145	14.54	1186	N	

HIGH REALISM TEST ARTICLE
JP-4 STREAM, LOCATION 5 (VAR. FLOW) AND 6, 2/8/88

LOCATION 5, 1.5 ML/S					
0.89	164	14.55	1198	F	3.3
0.97	152	14.55	1145	F	3.1

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.02	116	14.55	1088	N	
1.04	136	14.55	1091	N	
1.01	151	14.55	1092	F	2.6
0.96	104	14.54	1045	N	
1.01	122	14.54	1044	N	
1.00	131	14.54	1045	N	
LOCATION 6					
1.00	134	14.53	1168	N	
1.02	142	14.53	1203	N	
1.03	176	14.53	1250	F	6.7
1.01	144	14.52	1211	F	10
1.00	126	14.52	1161	N	
1.02	132	14.52	1160	N	
1.02	134	14.51	1161	N	
LOCATION 5, 3 ML/S					
0.99	95	14.51	1198	F	1.8
0.98	87	14.50	1145	F	3.9
0.99	88	14.50	1090	N	
1.00	103	14.50	1089	N	
1.00	107	14.50	1091	N	
HIGH REALISM TEST ARTICLE JP-4 STREAM, LOCATION 5 STRAIGHT ON CLAMP, 2/9/88					
1.02	136	14.47	1200	F	2.2
1.03	133	14.47	1144	F	4.6
1.03	123	14.47	1089	N	
1.03	127	14.47	1091	N	
1.03	136	14.47	1091	N	
1.01	154	14.46	1090	N	
1.00	96	14.46	846	N	
0.99	106	14.46	844	N	
0.99	110	14.46	844	N	
HIGH REALISM TEST ARTICLE 7808 SPRAY FROM UPSTREAM					
1.01	116	14.45	1250	no	
1.03	126	14.45	1302	yes	6.2
1.05	149	14.45	1333	yes	3.4
1.04	139	14.45	1303	yes	4.9
1.00	105	14.45	1253	no	
1.01	118	14.45	1253	yes	4.6

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.01	99	14.44	1205	no	
1.02	114	14.44	1203	no	
1.03	122	14.44	1202	no	
1.04	131	14.45	1203	no	

HIGH REALISM TEST ARTICLE
7808 STREAM, LOCATION 1,2,3,4,5 , 2/12/88

position 1		PNACIN			
1.01	144	14.37	1124	N	
1.02	168	14.37	1132	N	
1.03	175	14.37	1097	N	
position 2, 11.8 sec					
1.02	159	14.37	1214	F	2.3
1.01	134	14.37	1175	F	31.9
1.01	121	14.37	1129	N	
1.01	146	14.37	1128	N	
1.02	159	14.37	1127	N	
position 3					
1.01	160	14.37	1237	F	2.5
0.99	140	14.37	1188	F	2.4
1.01	140	14.37	1136	F	2.3
1.00	126	14.37	1089	F	3.3
1.00	112	14.37	1039	N	
1.00	122	14.37	1038	F	7.5
0.99	137	14.36	993	F	9.2
1.01	107	14.36	936	N	
1.01	128	14.37	939	N	
1.01	138	14.36	937	N	
position 4					
1.01	155	14.36	1132	N	
1.04	157	14.36	1236	F	2.2
1.03	127	14.36	1191	N	
1.03	152	14.36	1191	N	
1.03	164	14.36	1192	N	
position 5					
0.98	132	14.36	1236	F	2.1
1.01	127	14.36	1188	F	4.2
1.02	106	14.36	1140	N	
1.01	118	14.36	1138	N	
1.00	133	14.36	1137	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE					
7808 STREAM, LOCATION 6 AND 3, 2/17/88					
location 6					
1.03	154	14.42	1240	N	
0.88	165	14.42	1246	N	
1.04	173	14.42	1235	N	
location 3					
2.00	109	14.41	1088	F	3.1
2.04	115	14.41	1037	F	7.8
2.00	117	14.41	991	F	14.3
2.02	116	14.41	938	N	
1.99	112	14.41	936	N	
1.99	111	14.41	939	N	
4.02	106	14.41	1150	F	2
4.08	114	14.41	1088	F	8.3
3.99	120	14.41	1041	N	
4.05	124	14.41	1039	N	
4.04	128	14.41	1041	N	
5.96	132	14.41	1198	F	1.6
5.97	133	14.41	1134	F	1.8
5.91	131	14.40	1091	N	
6.00	132	14.40	1092	F	7.6
6.10	131	14.40	1040	N	
5.89	129	14.40	1043	N	
5.97	128	14.40	1039	N	
7.98	133	14.39	1205	F	1.7
7.89	129	14.39	1132	F	2.5
8.05	126	14.39	1085	N	
8.04	124	14.38	1088	N	
7.91	121	14.39	1090	N	
HIGH REALISM TEST ARTICLE					
7808 AND 83282 SPRAY FROM DOWNSTREAM, 2/19/88					
7808 SPRAY FROM DOWNSTREAM					
1.08	166	14.15	1310	F	2.6
1.01	133	14.15	1256	F	3.6
1.00	138	14.15	1207	F	5.8
0.98	121	14.15	1149	N	
1.02	142	14.15	1152	F	6.5
0.98	118	14.15	1107	N	
1.00	131	14.15	1104	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.01	136	14.15	1104	F	7
0.98	120	14.14	1054	N	
0.99	128	14.14	1052	N	
0.99	136	14.14	1052	N	
83282 spray from downstream					
1.01	140	14.13	1308	F	1.2
0.99	134	14.13	1253	F	4.1
0.97	124	14.13	1205	F	5.7
0.95	111	14.13	1156	F	5.8
0.98	120	14.13	1106	F	6.1
0.96	105	14.13	1056	F	5.7
0.96	97	14.13	1003	F	6
0.99	89	14.13	945	F	6.1
0.98	81	14.13	902	F	5.9
0.98	68	14.13	852	F	5.8
1.01	88	14.13	802	N	
1.01	101	14.13	796	N	
1.00	111	14.13	798	F	6.1
1.01	116	14.12	751	N	
1.00	120	14.12	749	N	
1.00	128	14.12	753	N	
83282 spray from upstream					
1.00	120	14.11	1107	N	
0.98	120	14.12	1202	F	2.6
1.01	127	14.11	1155	N	
1.02	136	14.11	1153	F	6.1
1.01	140	14.11	1106	N	
1.00	148	14.11	1103	N	
1.02	156	14.11	1106	N	
1.01	171	14.11	1204	F	2.9
0.99	142	14.11	900	N	
0.99	147	14.10	907	N	
0.99	149	14.10	906	N	

HIGH REALISM TEST ARTICLE
83282 STREAM, LOCATION 1,2,3,4 , 2/22/88

location 1

1.25	147	14.41	994	N	
1.13	185	14.41	1083	N	
1.27	192	14.41	1122	N	
1.19	172	14.41	1131	N	
1.13	165	14.41	1153	F	2.5

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.10	154	14.41	1122	N	
1.07	148	14.41	1122	F	2.3
1.04	138	14.41	1087	N	
1.01	147	14.41	1077	N	
0.99	136	14.41	1075	F	14.3
1.01	150	14.41	1048	F	15
0.98	141	14.41	1003	N	
1.01	173	14.41	980	N	
1.02	193	14.40	982	N	
location 2					
0.93	131	14.40	1167	F	2.1
0.96	134	14.40	1124	F	1.9
1.00	166	14.40	1070	N	
1.00	184	14.40	1070	N	
1.00	191	14.39	1068	N	
location 3					
1.02	154	14.39	983	F	2.2
1.01	167	14.39	935	F	2.1
0.99	150	14.38	886	F	1.8
1.01	138	14.39	836	F	2
1.02	138	14.37	787	F	2.3
1.02	135	14.37	737	N	
1.02	154	14.37	739	N	
1.02	161	14.37	741	N	
location 4					
1.02	134	14.37	1104	N	
1.00	162	14.37	1201	F	12.2
1.00	169	14.36	1203	F	12.2
1.00	170	14.36	1143	N	
1.00	196	14.37	1143	N	
1.02	187	14.36	1141	N	

HIGH REALISM TEST ARTICLE
83282 STREAM, LOCATION 5, 6 AND 3, 2/23/88

location 5					
1.01	118	14.36	1197	F	1.6
1.05	156	14.36	1142	F	1.5
1.01	132	14.35	1093	F	1.6
1.00	117	14.36	1044	F	39.4
0.99	110	14.36	992	F	37.8
1.00	102	14.36	942	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
0.99	116	14.36	944	N	
1.00	130	14.36	945	N	
location 6					
1.03	192	14.36	1247	F	43
1.00	202	14.35	1247	F	2
0.98	158	14.35	1211	N	
0.99	177	14.35	1211	N	
1.02	188	14.35	1214	N	
location 3					
0.00	188	14.35	894	F	1.9
0.00	146	14.34	839	F	2
0.00	144	14.35	793	F	2.8
0.00	120	14.34	742	N	
0.00	127	14.34	743	N	
0.00	113	14.34	743	N	
1.98	114	14.34	891	F	1.9
2.04	129	14.34	839	F	2
2.01	99	14.33	792	N	
2.03	116	14.34	790	N	
2.02	126	14.34	793	N	
4.03	140	14.34	955	F	2
4.10	113	14.33	894	F	2
4.08	121	14.33	837	F	1.9
4.05	111	14.33	795	F	2.8
4.06	117	14.33	750	N	
3.91	128	14.33	747	N	
3.95	127	14.33	747	N	
6.14	138	14.33	957	F	2
6.12	132	14.33	892	F	2
6.10	132	14.33	841	F	2.4
6.05	131	14.33	797	N	
5.97	132	14.32	793	N	
5.99	132	14.32	795	N	

HIGH REALISM TEST ARTICLE
83282 STREAM, LOCATION 3, SPRAY FROM UPSTREAM AND SPRAY FROM DOWNSTREAM
2/24/88

location 3					
8.25	103	14.44	942	N	
7.76	114	14.44	1051	F	2.1
8.03	116	14.44	994	F	1.8
7.93	117	14.44	946	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
7.98	118	14.44	944	F	6.4
8.01	116	14.44	895	F	2.6
8.06	116	14.43	846	F	2.4
7.89	115	14.43	797	N	
7.91	115	14.43	793	N	
7.80	116	14.43	796	N	
spray from upstream					
1.01	99	14.43	1203	F	3
1.01	119	14.42	1156	F	5.2
1.01	122	14.43	1104	N	
1.01	128	14.43	1099	N	
1.01	130	14.43	1099	N	
1.01	135	14.43	1150	F	5.8
spray from downstream					
2.04	82	14.41	1002	F	6.2
1.99	80	14.42	957	N	
2.00	83	14.42	954	N	
1.99	90	14.42	954	N	
3.99	99	14.42	1108	F	5.5
4.04	103	14.42	1056	F	6
4.04	100	14.42	1007	F	5.7
4.00	100	14.42	953	F	6.9
4.04	94	14.42	902	F	6
4.02	92	14.42	853	F	6.5
3.94	87	14.42	805	F	6.8
3.88	86	14.42	753	N	
3.97	100	14.42	756	N	
4.07	103	14.41	746	F	6.5
3.92	84	14.41	707	N	
3.97	99	14.42	699	N	
3.99	106	14.41	695	N	
2.00	111	14.42	957	F	5.9
2.03	103	14.41	902	F	7
1.91	80	14.42	852	N	
1.97	89	14.42	851	N	
1.98	100	14.42	850	F	2.8
1.94	82	14.41	805	N	
1.98	91	14.42	806	N	
2.03	97	14.41	805	N	
1.98	103	14.42	804	N	
2.02	108	14.42	805	F	5.9
1.97	88	14.42	754	N	
1.97	95	14.42	751	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.97	100	14.41	750	N	
2.01	102	14.41	749	N	
2.00	107	14.41	749	N	
1.98	108	14.41	749	N	

HIGH REALISM TEST ARTICLE
83282 SPRAY FROM DOWNSTREAM, 2/25/88

0.00	114	14.44	903	F	6.1
0.00	118	14.44	853	F	1.2
0.00	132	14.44	798	F	6.6
0.00	96	14.44	754	F	4.2
0.00	100	14.44	703	N	
0.00	119	14.44	696	N	
0.00	97	14.43	701	N	
0.95	97	14.43	858	F	3.4
0.99	104	14.43	804	N	
1.00	108	14.43	794	F	6.2
1.01	106	14.43	752	N	
0.99	109	14.43	743	N	
1.00	110	14.43	748	N	
6.08	96	14.43	855	N	
6.00	111	14.43	907	N	
5.93	120	14.43	950	F	6.8
6.00	122	14.42	901	F	5.9
5.94	120	14.43	848	F	5.8
6.04	123	14.43	799	N	
6.02	129	14.42	796	N	
5.98	129	14.42	805	F	6.5
5.84	125	14.42	751	N	
5.80	127	14.42	753	N	
5.97	127	14.42	750	N	
8.20	125	14.42	1008	F	6
7.97	121	14.42	955	N	
7.94	123	14.42	949	N	
8.10	123	14.42	946	N	
26.19	110	14.42	1228	N	
20.84	110	14.41	1289	F	5.7
20.12	105	14.41	1242	F	5.9
19.10	104	14.41	1215	N	
19.84	105	14.41	1201	N	
20.37	105	14.41	1199	N	

HIGH REALISM TEST ARTICLE
JP-8 SPRAY FROM DOWNSTREAM AND SPRAY FROM UPSTREAM, 2/26/88

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
spray from downstream					
1.08	142	14.38	1209	F	6.1
1.01	153	14.37	1155	F	5.8
1.02	161	14.38	1106	N	
1.04	160	14.37	1105	N	
1.03	167	14.37	1105	N	
1.05	186	14.37	1153	N	
1.03	156	14.36	1198	F	5.7
1.01	150	14.36	1159	F	5.7
0.98	145	14.36	1105	N	
0.98	150	14.36	1099	N	
0 98	156	14.36	1099	N	
0.00	170	14.36	1097	N	
0.00	158	14.36	1100	N	
0.00	131	14.35	1101	N	
2.02	132	14.35	1105	F	5.7
2.04	142	14.34	1054	N	
2.00	146	14.35	1052	N	
1.99	147	14.34	1051	N	
3.92	130	14.34	1051	N	
4.01	121	14.34	1050	N	
3.97	117	14.34	1051	N	
spray from upstream					
1.01	125	14.33	1306	F	1.5
1.01	120	14.33	1256	F	3.2
1.00	109	14.33	1205	F	2.9
1.00	101	14.33	1155	N	
1.01	120	14.33	1152	N	
1.02	132	14.33	1152	N	
1.01	108	14.33	1150	N	
2.00	92	14.32	1154	N	
1.96	100	14.32	1153	N	
2.00	105	14.32	1154	F	6.1
2.01	106	14.32	1106	N	
2.02	111	14.32	1102	N	
2.02	114	14.32	1102	N	
0.00	158	14.32	1098	N	
0.00	123	14.31	1099	N	
0.00	114	14.31	1098	N	

HIGH REALISM TEST ARTICLE
JP-8 STREAM, LOCATION 1,2,3,4 , 2/29/88

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
LOCATION 1					
1.04	176	14.45	1174	F	1.2
1.02	159	14.45	1119	F	1.4
1.02	164	14.44	1090	F	1.2
1.01	162	14.44	1040	F	1.2
1.01	157	14.44	1005	F	1.7
0.99	135	14.44	946	F	3.2
0.98	122	14.43	903	F	3.7
1.01	119	14.43	866	N	
1.02	134	14.43	848	F	6
0.99	121	14.43	820	N	
1.00	133	14.43	799	F	9
0.99	119	14.42	783	N	
1.00	131	14.43	773	N	
0.99	138	14.42	769	N	
LOCATION 2					
1.03	131	14.42	976	N	
1.01	158	14.42	1077	F	12.6
1.00	144	14.42	1022	F	1.2
1.02	129	14.42	973	N	
1.01	146	14.42	976	N	
1.00	153	14.41	976	N	
0.98	157	14.41	975	N	
1.00	165	14.41	1073	N	
1.00	186	14.41	1161	F	2.6
LOCATION 3					
1.00	144	14.40	992	F	1.6
0.99	119	14.41	941	F	2.4
1.03	119	14.40	891	F	3
1.03	109	14.40	845	N	
1.01	133	14.40	843	F	4.5
1.01	121	14.40	799	N	
1.00	132	14.41	798	N	
1.01	146	14.40	796	N	
LOCATION 4					
1.00	131	14.40	992	N	
1.01	159	14.41	1103	N	
1.02	192	14.40	1204	F	1.4
0.99	152	14.40	1145	F	2.3
1.02	136	14.40	1096	F	3.4
1.01	125	14.40	1052	F	13

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE					
JP-8 STREAM, LOCATION 2,4,5,6 , 3/1/88					
LOCATION 2					
1.03	131	14.50	1173	F	1.9
1.04	147	14.50	1121	F	2.8
1.04	141	14.50	1078	N	
1.03	174	14.48	1077	F	3.2
1.03	159	14.48	1029	F	3.1
1.01	139	14.48	980	N	
1.02	163	14.47	979	N	
1.01	173	14.47	979	F	3.2
0.98	115	14.47	930	N	
1.00	134	14.46	930	N	
1.01	147	14.47	931	N	
1.01	159	14.46	735	N	
1.01	166	14.46	734	N	
1.00	168	14.46	735	N	
LOCATION 4					
1.00	160	14.46	1209	N	
1.01	190	14.46	1254	F	3.1
1.00	171	14.46	1191	F	4.7
1.00	158	14.46	1142	N	
1.02	187	14.45	1143	N	
1.01	199	14.46	1146	F	4.6
1.01	158	14.45	1095	N	
1.02	192	14.45	1095	F	3.5
1.01	151	14.45	1047	N	
1.02	182	14.45	1045	N	
1.00	193	14.45	1047	N	
LOCATION 5					
0.99	155	14.44	1193	F	2.4
0.99	157	14.44	1137	F	5
1.04	154	14.45	1092	F	6.5
1.04	148	14.44	1041	N	
1.00	177	14.44	1041	N	
0.99	190	14.44	1044	N	
LOCATION 6					
0.99	123	14.44	1171	N	
1.00	144	14.43	1263	F	7.9
1.01	155	14.43	1206	N	
1.00	170	14.43	1207	F	6.8

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.00	144	14.43	1164	N	
1.02	152	14.43	1158	N	
1.02	152	14.43	1158	N	
1.00	150	14.42	1154	F	9.6

HIGH REALISM TEST ARTICLE
JP-8 STREAM, LOCATION 6 AND 1, 3/2/88

LOCATION 6

1.00	128	14.36	1177	N	
1.02	148	14.36	1236	N	
1.03	118	14.35	1259	N	
1.02	169	14.34	1305	F	1.9
1.01	163	14.34	1250	F	3.2
1.03	146	14.34	1207	N	
1.01	176	14.34	1209	F	3.7
1.01	150	14.34	1162	F	4.4
1.01	143	14.34	1118	N	
1.00	172	14.35	1113	N	
0.97	184	14.34	1110	N	

LOCATION 1

0.00	138	14.34	896	F	2.2
0.00	142	14.34	860	F	2.1
0.00	151	14.34	829	N	
0.00	168	14.33	815	N	
0.00	174	14.33	815	N	
2.00	124	14.34	912	F	3.1
2.01	106	14.34	875	F	3.7
1.95	99	14.34	834	N	
1.97	109	14.35	816	F	2.7
1.98	87	14.35	784	F	3.4
2.03	86	14.36	749	N	
1.99	91	14.35	723	N	
1.98	96	14.36	716	N	
4.08	110	14.36	906	N	
4.01	122	14.35	940	N	
3.96	127	14.35	955	F	11.2
3.99	129	14.35	965	N	
3.97	130	14.35	951	N	
4.02	131	14.35	952	N	
6.07	129	14.35	1162	F	5.4
6.02	128	14.35	1135	F	7.8
5.81	129	14.35	1097	N	
6.00	126	14.35	1080	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
5.89	126	14.34	1079	N	

HIGH REALISM TEST ARTICLE
JP-8 STREAM, LOCATION 1, JP-4 STREAM, LOCATION 1, 3/3/88

JP-8, LOCATION 1

8.23	120	14.34	1161	F	1.5
8.05	121	14.34	1130	F	2.6
7.94	120	14.34	1097	F	2.2
8.01	120	14.34	1054	F	3.6
8.15	122	14.34	1010	N	
8.11	122	14.34	997	N	
7.91	120	14.33	992	N	
6.01	124	14.33	1122	F	2
6.00	123	14.33	1099	F	2.3
5.91	120	14.33	1058	F	3.7
6.01	119	14.33	1020	N	
5.99	120	14.33	996	N	
6.04	118	14.33	992	N	

JP-4, LOCATION 1

0.00	132	14.32	1125	F	3.5
0.00	123	14.32	1090	F	4.5
0.00	133	14.32	1082	F	3
0.00	141	14.32	1037	F	4.2
0.00	133	14.32	991	N	
0.00	159	14.32	981	N	
0.00	176	14.32	979	N	
1.96	145	14.32	1164	F	4
2.04	130	14.32	1123	F	3.2
2.01	121	14.32	1085	F	4.8
2.01	118	14.32	1038	N	
2.04	131	14.32	1029	N	
2.02	142	14.31	1033	N	
4.06	111	14.31	1140	N	
4.03	126	14.31	1164	F	3
3.98	133	14.31	1137	N	
3.99	131	14.31	1124	F	10.4
3.95	130	14.31	1104	N	
4.08	130	14.31	1086	N	
4.04	132	14.31	1080	N	

HIGH REALISM TEST ARTICLE
JP-4 STREAM, LOCATION 1, 3/4/88

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
6.05	111	14.35	1155	F	3.8
6.00	113	14.36	1136	F	7.2
5.98	118	14.36	1102	F	9.4
5.94	120	14.35	1060	F	12.4
6.01	115	14.36	1014	N	
5.96	116	14.36	1001	N	
5.99	118	14.35	999	N	
7.97	120	14.35	1167	F	9.1
8.21	125	14.35	1143	N	
8.01	126	14.34	1125	N	
8.10	125	14.34	1125	F	12
8.16	125	14.34	1104	N	
7.92	128	14.34	1089	N	
8.02	126	14.34	1090	N	
6.05	112	14.34	1167	F	10.8
5.97	117	14.34	1134	N	
5.94	117	14.34	1119	N	
6.04	115	14.33	1137	N	
5.97	114	14.34	1136	N	
6.06	113	14.34	1130	N	
6.08	114	14.34	1135	N	

HIGH REALISM TEST ARTICLE
JP-4 STREAM, LOCATION 1, 3/7/88

4.03	114	14.47	1169	F	1.6
4.04	123	14.49	1146	F	8.1
4.02	133	14.49	1110	F	10.8
4.02	140	14.50	1067	N	
4.00	144	14.50	1054	F	13.5
4.03	144	14.50	1021	N	
3.99	143	14.49	1005	N	
3.99	139	14.47	1010	N	
6.06	124	14.45	1157	F	10
5.97	126	14.42	1142	N	
6.01	129	14.42	1127	N	
5.97	129	14.43	1137	N	
5.88	131	14.41	1177	F	11
8.16	124	14.41	1162	N	
8.01	125	14.41	1177	F	13.9
8.11	121	14.41	1156	N	
7.87	119	14.41	1138	N	
8.01	117	14.41	1136	N	
4.02	151	14.40	1178	F	1.9
3.99	141	14.40	1149	F	2.4

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
3.96	129	14.41	1100	F	13.1
3.93	124	14.40	1064	N	
4.01	129	14.40	1050	N	
3.99	127	14.40	1047	N	
2.05	185	14.40	1134	F	2.8
2.01	194	14.39	1113	F	9.7
2.00	197	14.40	1071	F	13.3
1.99	187	14.39	1026	N	
2.00	184	14.40	1013	F	14.4
1.96	178	14.38	968	N	
1.98	171	14.38	956	N	
2.00	169	14.38	962	N	

HIGH REALISM TEST ARTICLE
JP-4 STREAM, LOCATION 1, 83282 STREAM, LOCATION 3, 3/8/88

0.00	170	14.42	1076	F	13.2
0.00	161	14.42	1038	N	
0.00	180	14.42	1040	N	
0.00	195	14.42	1039	N	
1.01	174	14.42	1080	N	
1.03	207	14.42	1125	F	11.4
1.01	170	14.42	1072	N	
1.03	194	14.42	1082	N	
1.01	210	14.42	1082	N	

83282, LOCATION 3

1.83	583	14.40	1000	F	0.4
2.03	621	14.39	959	F	0.4
2.01	638	14.38	903	F	0.4
1.95	622	14.39	860	F	0.4
1.94	624	14.39	805	F	0.4
1.91	624	14.38	748	F	0.4
1.95	627	14.38	697	F	0.8
1.97	631	14.39	655	F	0.6
1.97	627	14.38	609	F	0.7
1.93	585	14.39	547	N	
1.98	502	14.39	552	N	
2.08	481	14.39	557	N	
2.25	631	14.38	558	N	
2.02	612	14.38	555	N	
2.05	650	14.38	599	N	
1.98	645	14.37	650	F	1.8
2.03	671	14.37	615	F	2.9
2.02	656	14.37	555	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
1.98	599	14.38	540	N	
2.12	658	14.37	553	N	

HIGH REALISM TEST ARTICLE
83282 STREAM, LOCATION 3, 83282 SPRAY FROM DOWNSTREAM, 3/15/88

LOCATION 3					
1.97	313	14.34	917	F	2.3
1.95	314	14.34	855	F	2.3
1.97	316	14.34	804	F	2.4
1.98	315	14.34	751	F	2.6
1.99	315	14.34	702	N	
2.04	322	14.34	698	N	
2.03	329	14.33	702	N	
line full					
2.08	331	14.34	703	F	2.3
2.04	331	14.33	702	N	
2.05	332	14.33	702	N	
2.02	335	14.33	703	F	1.6
2.00	316	14.33	646	N	
2.03	322	14.33	648	N	
2.11	332	14.33	647	F	3
2.08	321	14.33	597	N	
2.12	329	14.33	596	N	
2.11	332	14.32	596	N	
SPRAY FROM DOWNSTREAM					
2.02	301	14.32	914	F	1.1
1.97	288	14.32	853	F	4.1
1.98	283	14.32	803	F	3.1
2.00	284	14.32	755	F	2.2
2.01	295	14.32	706	F	2.2
2.05	314	14.32	652	F	6.6
2.08	322	14.32	599	N	
2.10	331	14.32	601	N	
2.09	341	14.32	603	N	

HIGH REALISM TEST ARTICLE
JP-4, JP-8 STREAM AT LOCATION 5 AND SPRAY FROM DOWNSTREAM, 3/31/88

JP-4, LOCATION 5					
2.00	290	14.51	1208	F	6.7
2.02	296	14.51	1152	N	
2.07	307	14.51	1147	N	
2.07	316	14.51	1144	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
full line					
2.07	323	14.50	1145	F	8.5
2.02	318	14.51	1090	N	
2.03	312	14.50	1086	N	
2.03	308	14.50	1083	N	
JP-4, SPRAY FROM DOWNSTREAM					
2.02	283	14.50	1207	F	5.5
2.02	290	14.50	1154	F	5.9
2.00	288	14.50	1105	F	6.8
1.99	294	14.49	1059	N	
2.08	301	14.49	1051	F	6.6
2.01	296	14.49	1007	N	
2.00	285	14.49	1001	N	
2.01	293	14.50	1004	N	
JP-8, LOCATION 5					
2.03	286	14.49	1194	F	4.6
2.04	294	14.49	1145	F	6.6
2.02	297	14.50	1097	F	7.8
2.03	299	14.50	1043	F	8.8
2.00	298	14.50	997	N	
2.01	301	14.49	988	F	11.6
2.03	295	14.49	946	N	
2.00	296	14.48	947	N	
2.04	299	14.49	944	F	8.9
2.02	302	14.49	899	N	
1.97	299	14.49	890	N	
1.99	303	14.49	890	N	
line full					
1.99	304	14.49	892	N	
1.99	308	14.49	895	N	
1.97	312	14.49	892	N	
JP-8, SPRAY FROM DOWNSTREAM					
2.05	280	14.49	1216	F	2.4
2.03	286	14.49	1161	F	5.7
2.04	295	14.49	1108	F	6.2
1.99	300	14.49	1054	F	6.7
2.01	300	14.49	1002	F	6.9
2.04	294	14.49	952	F	7
2.00	295	14.49	902	N	
2.07	293	14.49	895	N	
1.99	306	14.49	899	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
HIGH REALISM TEST ARTICLE					
7808, SPRAY FROM DOWNSTREAM, 3/31/88					
2.00	282	14.49	1210	F	2.2
2.03	292	14.48	1154	F	4.1
2.03	296	14.49	1100	N	
1.98	294	14.48	1101	F	6.1
1.92	289	14.48	1056	F	7.1
2.01	287	14.48	1008	N	
2.01	289	14.49	1002	N	
2.08	298	14.48	1000	N	
HIGH REALISM TEST ARTICLE					
7808 AND 5606 STREAM, LOCATION 3, 5606 SPRAY FROM DOWNSTREAM, 4/1/88					
7808, LOCATION 3					
2.04	289	14.43	1097	F	1.7
2.03	296	14.43	1047	N	
2.01	294	14.43	1044	F	9
1.99	303	14.43	1001	N	
1.98	301	14.43	998	N	
1.99	303	14.43	993	N	
line full					
1.97	303	14.43	993	N	
2.00	307	14.43	995	N	
2.02	307	14.43	997	N	
5606, LOCATION 3					
1.99	293	14.43	1000	F	1.7
2.00	294	14.43	945	F	1.6
1.98	294	14.43	901	F	3.5
2.03	296	14.43	849	F	1.4
2.01	292	14.42	796	F	2
1.99	286	14.43	749	F	1.7
2.01	289	14.42	695	F	13.9
1.95	293	14.43	644	F	18.6
1.97	293	14.42	596	N	
1.99	293	14.42	592	N	
1.98	301	14.42	598	N	
line full					
2.00	303	14.42	600	N	
1.97	294	14.42	599	N	
1.99	301	14.42	598	N	

5606 SPRAY FROM DOWNSTREAM

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
2.01	287	14.41	1211	F	4.2
2.01	290	14.42	1158	F	5.8
2.03	295	14.42	1104	F	6
2.04	294	14.41	1054	F	6.4
2.05	295	14.41	1002	F	6.3
2.03	296	14.41	952	F	6.4
2.00	293	14.41	901	F	6.3
2.01	293	14.41	853	F	6.1
2.02	296	14.41	802	F	6.4
2.01	296	14.40	749	F	7.3
2.03	300	14.41	697	F	6.5
2.01	297	14.40	647	N	
1.92	289	14.41	646	N	
2.00	300	14.40	647	N	
5606 SPRAY FROM DOWNSTREAM					
1.97	559	14.40	798	F	6.2
2.04	556	14.40	742	F	6.3
2.05	562	14.39	698	F	6.5
2.02	557	14.40	648	F	6.7
2.03	568	14.40	597	F	7.8
2.01	530	14.40	541	N	
1.95	593	14.39	550	N	
2.00	576	14.40	550	N	
1.95	572	14.39	549	N	
0.00	599	14.40	549	F	
0.00	601	14.39	497	F	
0.00	593	14.39	445	F	
0.00	595	14.39	401	F	
0.00	574	14.38	416	F	

HIGH REALISM TEST ARTICLE
5606 AND 7808 STREAM AT LOCATION 308 AND JP-8 SPRAY FROM DOWNSTREAM (4/4/88)

5606. LOCATION 3

1.98	581	14.31	794	F	2
1.96	554	14.31	739	F	2.3
1.99	566	14.31	695	F	2.8
2.01	572	14.30	646	F	12
1.99	569	14.30	598	F	2.6
1.99	576	14.30	552	N	
1.97	579	14.30	551	N	
1.98	584	14.29	550	N	

full line

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
2.00	600	14.30	550	N	
2.02	626	14.29	551	N	
2.01	611	14.29	551	N	
0.00	614	14.29	550	N	
7808, LOCATION 3					
1.99	582	14.29	994	F	1.2
1.98	591	14.29	949	F	1.3
1.99	605	14.29	903	F	1.9
1.99	596	14.29	853	F	1.9
1.98	577	14.29	800	N	
1.97	576	14.29	799	N	
2.05	589	14.29	798	N	
full line					
2.09	598	14.29	798	N	
7808 SPRAY FROM DOWNSTREAM					
2.07	562	14.29	1106	F	6
2.05	546	14.28	1054	F	6.2
2.02	546	14.28	1002	F	6.8
2.07	560	14.28	950	N	
2.06	575	14.28	950	F	7.2
2.05	584	14.28	900	N	
2.03	585	14.28	899	N	
2.07	594	14.28	903	N	
JP-8 SPRAY FROM DOWNSTREAM					
2.00	549	14.27	1210	F	2
1.99	537	14.27	1157	F	2.1
2.02	537	14.28	1105	F	2.2
2.00	526	14.28	1049	F	2.4
1.99	522	14.27	999	F	2.9
2.00	534	14.27	949	F	3.1
2.04	547	14.27	895	F	3.8
2.05	564	14.27	847	F	5.2
2.03	556	14.27	798	F	5.9
2.06	565	14.27	748	F	6.6
2.03	564	14.27	697	F	7.1
1.99	572	14.27	649	N	
2.04	582	14.27	651	F	
2.01	585	14.27	595	N	
2.01	595	14.27	597	F	7.2
1.99	590	14.27	548	N	
1.99	591	14.27	547	N	
2.00	598	14.27	553	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
0.00	615	14.27	550	F	

HIGH REALISM TEST ARTICLE
JP-8 STREAM, LOCATION 5, 83282 STREAM AT LOCATION 3 AND SPRAY FROM DOWNSTREAM AND JP-4 SPRAY FROM DOWNSTREAM, 4/5/88

JP-8, LOCATION 5					
2.06	571	14.30	991	N	
2.05	568	14.30	1090	F	7.9
2.04	574	14.30	1043	F	8.7
2.02	572	14.29	995	N	
2.02	565	14.29	989	N	
2.00	562	14.29	998	N	
full line					
2.04	575	14.29	997	N	
83282, LOCATION 3					
2.02	557	14.27	789	F	2.3
2.03	558	14.28	746	F	2.4
2.01	567	14.28	691	F	2.6
2.06	578	14.28	646	F	3.9
2.08	591	14.28	597	F	4.4
2.05	601	14.27	545	N	
2.02	596	14.28	548	N	
2.02	608	14.26	549	N	
full line					
2.09	621	14.27	549	N	
83282, SPRAY FROM DOWNSTREAM					
1.99	582	14.27	698	F	2.4
2.01	582	14.26	645	F	2.5
2.00	581	14.27	597	F	2.9
2.06	582	14.26	548	F	3.3
2.04	588	14.26	493	F	3.6
JP-4, SPRAY FROM DOWNSTREAM					
2.00	550	14.26	1101	F	2.9
2.03	540	14.26	1056	F	3.1
2.03	545	14.26	1006	F	4.5
2.00	556	14.26	947	F	5.8
2.10	561	14.26	905	F	6.4
2.06	551	14.26	849	F	6.7
2.08	552	14.26	802	F	7.6
2.07	567	14.25	752	N	
2.07	571	14.25	750	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
2.15	593	14.25	753	F	
2.03	575	14.25	700	N	
2.02	575	14.24	700	N	
2.03	594	14.24	701	N	
0.00	604	14.24	700	F	7.1

HIGH REALISM TEST ARTICLE
JP-4, JP-8 STREAM AT LOCATION 5 AND SPRAY FROM DOWNSTREAM, 4/7/88

JP-4, LOCATION 5					
2.10	119	14.25	1174	N	
2.16	137	14.25	1296	F	5.2
2.10	137	14.25	1246	F	3.7
2.06	132	14.25	1195	N	
2.09	130	14.25	1181	F	
2.04	127	14.25	1137	N	
2.05	129	14.25	1131	N	
2.03	125	14.24	1131	N	
JP-4 SPRAY FROM DONWSTREAM					
2.15	117	14.24	1319	F	2.4
2.11	121	14.24	1264	F	2.7
2.00	111	14.24	1208	F	5.5
1.96	110	14.24	1162	F	6.5
1.93	105	14.23	1106	N	
1.99	108	14.24	1098	N	
1.96	105	14.23	1097	N	
JP-8 SPRAY FROM DOWNSTREAM					
2.04	129	14.23	1313	F	2
2.01	124	14.23	1256	F	2.4
1.96	118	14.23	1205	F	1.9
1.99	117	14.23	1153	F	5.9
1.99	113	14.23	1101	F	6
2.00	115	14.23	1056	N	
1.99	117	14.23	1048	N	
1.99	117	14.24	1051	N	
JP-8, LOCATION 5					
1.93	101	14.23	1188	F	4.8
1.97	101	14.23	1138	N	
2.05	109	14.23	1130	N	
2.04	113	14.23	1131	F	
2.00	103	14.24	1089	N	
2.02	109	14.23	1082	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
2.00	109	14.24	1003	N	
HIGH REALISM TEST ARTICLE 5606, 7808 SPRAY FROM DOWNSTREAM, 7808 STREAM AT LOCATION 3 JP-4, JP-8 STREAM AT LOCATION 5, 4/8/88					
5606 SPRAY FROM DOWNSTREAM					
2.03	107	14.41	1214	F	4
2.07	112	14.40	1162	F	2.9
2.06	107	14.40	1100	F	5.9
2.01	103	14.40	1052	F	6.2
2.02	102	14.40	1003	N	
2.02	109	14.40	998	F	6.3
1.96	102	14.39	953	F	6.3
1.97	97	14.39	900	F	6.8
1.95	95	14.38	851	F	6.7
1.96	101	14.38	800	N	
1.98	112	14.38	793	F	6.5
1.95	107	14.38	752	F	7
1.93	104	14.37	702	N	
1.97	107	14.37	700	N	
1.96	108	14.37	703	N	
7808 SPRAY FROM DOWNSTREAM					
1.95	121	14.36	1108	F	6.6
1.95	101	14.36	1057	N	
1.96	110	14.36	1060	N	
1.99	115	14.36	1058	F	
1.97	110	14.36	1008	N	
2.01	116	14.36	1003	N	
2.01	119	14.36	1002	N	
7808, LOCATION 3					
2.02	316	14.36	1092	F	3.7
2.04	316	14.36	1042	N	
2.08	323	14.36	1044	F	8.1
2.02	326	14.36	993	N	
1.96	302	14.36	978	N	
1.94	305	14.36	991	N	
JP-8, LOCATION 5					
1.95	573	14.36	1092	F	5.6
2.05	569	14.36	1041	N	
1.98	554	14.36	1039	N	
2.00	572	14.36	1043	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
JP-4, LOCATION 5					
1.99	565	14.36	1136	N	
1.95	560	14.36	1244	F	3.1
2.00	571	14.35	1182	F	7
2.03	580	14.36	1138	N	
2.05	583	14.35	1140	N	
2.05	589	14.36	1141	N	

HIGH REALISM TEST ARTICLE
5606, 83282 STREAM AT LOCATION 3, JP-4 STREAM AT LOCATION 5,
VENTILATION AIR PRESSURE TESTS 4/22/88

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE?	IGNITION DELAY
5606, LOCATION 3					
2.18	118	9.83	999	N	
2.08	119	10.49	1201	F	1.5
2.18	137	10.15	1147	N	
2.22	153	10.06	1150	F	2.3
2.04	136	10.12	1103	N	
2.10	157	10.05	1092	N	
2.04	166	10.06	1098	N	
1.95	118	10.26	1185	F	2.7
1.98	121	10.25	1144	F	8.6
2.02	120	10.17	1095	F	7.5
1.94	116	10.15	1042	N	
2.06	138	10.06	1039	N	
2.04	149	10.02	1043	N	
1.99	138	5.22	1327	N	
2.11	143	4.76	1317	N	
1.90	155	5.37	1324	F	2.5
2.04	120	5.38	1298	N	
1.99	137	5.37	1293	N	
2.0	152	5.17	1290	N	
JP-4, LOCATION 5					
2.13	98	4.95	1324	N	
2.05	116	5.09	1309	N	
2.03	127	5.04	1308	N	
2.00	134	5.04	1303	N	
2.00	133	10.14	1337	F	3.5
2.04	125	10.18	1277	F	3.4
2.05	121	10.19	1237	N	
1.99	138	10.13	1213	F	7.5
2.03	123	10.02	1190	N	
2.08	143	9.97	1173	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
2.02	149	10.03	1177	N	
83282, LOCATION 3					
2.12	95	9.71	1193	F	2.6
1.97	95	10.24	1147	F	12.6
1.97	96	10.31	1096	N	
2.02	110	10.23	1093	N	
2.05	119	10.08	1094	N	
2.01	126	5.22	1350	F	2.9
1.99	123	5.28	1296	N	
2.02	142	5.17	1286	N	
1.97	155	5.07	1262	N	

HIGH REALISM TEST ARTICLE
7808 AND 5606 STREAM AT LOCATION 3;
7808, JP-4, 83282, JP-8, 5606 SPRAY FROM DOWNSTREAM;
JP-8 STREAM AT LOCATION 5,
VENTILATION AIR PRESSURE TESTS 4/25/88

7808, LOCATION 3					
2.11	126	10.18	1294	N	
2.09	136	10.1[illegible]	1341	N	
1.99	181	10.30	1341	F	2.1
1.97	171	10.29	1290	N	
1.89	160	10.18	1281	N	
1.91	155	10.11	1287	N	
2.29	127	5.03	1335	N	
2.02	160	5.29	1332	N	
2.01	175	5.23	1333	N	
7808 SPRAY FROM DOWNSTREAM					
1.97	114	10.07	1359	N	
2.12	144	10.0[illegible]	1355	N	
2.05	165	10.0[illegible]	1347	N	
2.56	133	4.98	1354	N	
2.05	165	5.06	1344	N	
1.97	187	5.12	1349	N	
JP-4 SPRAY FROM DOWNSTREAM					
2.13	145	10.06	1352	N	
2.17	222	10.02	1347	N	
1.94	260	10.09	1349	N	
2.19	155	5.01	1349	N	
2.15	229	5.11	1345	N	
2.03	266	5.09	1342	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
83282 SPRAY FROM DOWNSTREAM					
1.98	102	9.98	1340	N	
2.08	161	10.00	1348	N	
2.03	188	10.15	1353	N	
1.86	137	14.38	1362	F	---
2.07	147	5.05	1341	N	
2.00	169	5.13	1349	N	
1.91	187	5.22	1353	N	
JP-8, LOCATION 5					
1.88	83	10.08	1346	N	
2.04	113	10.01	1340	N	
2.04	133	10.20	1334	N	
2.07	161	14.37	1340	F	---
2.18	123	5.01	1343	N	
2.00	141	5.11	1317	N	
2.03	159	5.04	1317	N	
JP-8 SPRAY FROM DOWNSTREAM					
1.81	129	14.37	1364	F	
1.93	133	10.05	1362	N	
2.07	187	10.06	1364	N	
2.08	213	10.13	1361	N	
2.07	122	5.04	1362	N	
2.02	147	5.07	1360	N	
2.08	180	5.05	1358	N	
5606 SPRAY FROM DOWNSTREAM					
2.11	125	10.08	1367	N	
2.12	148	10.05	1359	N	
2.03	164	10.16	1358	N	
2.19	127	5.10	1352	N	
2.10	163	5.02	1351	N	
2.02	183	4.93	1353	N	
5606 SPRAY FROM DOWNSTREAM (LOW INJECTION PRESSURE)					
1.89	142	10.02	1366	N	
1.99	175	10.13	1365	N	
2.01	188	10.12	1364	N	
1.54	236	14.26	1348	F	---
5606 SPRAY FROM DOWNSTREAM					
10.83	76	19.71	1196	F	5.4
10.48	83	19.88	1147	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
10.15	75	19.83	1156	N	
10.17	74	19.83	1155	N	
JP-8, LOCATION 5					
11.67	77	20.18	1290	F	5.7
11.53	79	20.16	1239	F	8.5
10.97	75	20.32	1192	N	
10.82	74	20.16	1169	N	
10.74	72	20.14	1160	N	
JP-8 SPRAY FROM DOWNSTREAM					
11.43	73	20.58	1200	N	
11.25	71	20.18	1310	N	
11.05	71	20.07	1345	F	5.5
10.94	73	20.24	1312	F	3.2
10.82	73	20.15	1247	F	5.5
10.87	74	20.01	1208	N	
10.70	72	20.15	1205	N	
10.68	71	20.14	1204	N	
5606, LOCATION 3					
11.05	77	19.99	1170	F	5.8
10.93	75	20.01	1129	F	5.1
11.06	78	19.89	1079	F	6
10.98	79	19.99	1033	N	
10.68	74	19.95	1029	N	
10.66	74	19.91	1029	N	

HIGH REALISM TEST ARTICLE
5606, 7808, 83282 STREAM AT LOCATION 3;
5606, JP-8, JP-4, 7808, 83282 SPRAY FROM DOWNSTREAM;
JP-8, JP-4 STREAM AT LOCATION 5; 4/26/88

5606, LOCATION 3					
11.81	70	14.50	1329	F	2.5
10.53	71	14.46	1291	F	3.3
11.58	70	14.47	1234	F	4.2
11.22	69	14.36	1192	F	7.6
11.78	70	14.35	1137	F	5.4
10.69	69	14.34	1091	N	
10.98	69	14.34	1085	N	
11.30	68	14.35	1083	N	
5606 SPRAY FROM DOWNSTREAM					
11.25	69	14.35	1300	F	5.7

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
11.54	70	14.35	1257	N	
9.80	69	14.34	1254	N	
10.77	70	14.34	1251	N	
JP-8, LOCATION 5					
11.44	79	14.34	1285	F	9.8
11.33	74	14.34	1224	F	5.3
12.37	74	14.35	1195	N	
11.39	73	14.34	1178	N	
10.70	73	14.33	1180	N	
JP-8 SPRAY FROM DOWNSTREAM					
10.93	76	14.34	1349	F	3.8
11.28	75	14.34	1303	N	
11.11	75	14.34	1293	F	5.9
10.58	74	14.33	1258	N	
9.82	75	14.33	1252	N	
9.00	74	14.32	1251	N	
JP-4, LOCATION 5					
10.97	83	14.32	1319	F	12.7
10.01	80	14.32	1291	N	
10.81	80	14.32	1264	N	
11.29	79	14.33	1263	N	
10.92	79	20.15	1281	F	6.4
10.81	78	20.03	1237	F	11.7
10.77	79	20.04	1192	N	
10.68	74	19.99	1171	N	
10.83	72	20.04	1165	N	
JP-4 SPRAY FROM DOWNSTREAM					
11.28	77	14.32	1344	F	2.3
11.47	77	14.31	1296	F	5.8
9.87	76	14.30	1247	N	
10.37	77	14.31	1239	N	
10.08	75	14.30	1237	N	
11.49	79	20.29	1229	N	
11.17	73	20.25	1290	F	4.1
11.29	89	20.16	1239	F	5.7
11.10	89	20.03	1193	N	
10.76	76	20.04	1190	N	
10.61	73	19.98	119[illegible]	N	
7808, LOCATION 3					
11.64	84	14.30	1293	F	2

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
12.27	92	14.30	1232	F	10
11.22	84	14.29	1189	N	
10.56	83	14.29	1186	N	
11.98	82	14.30	1184	N	
11.52	84	20.21	1183	F	2.3
11.50	86	20.10	1135	F	3.3
11.30	82	20.14	1081	N	
11.18	78	19.96	1091	N	
11.07	76	19.87	1099	N	
7808 SPRAY FROM DOWNSTREAM					
9.68	84	14.29	1290	F	6
9.75	79	14.29	1240	N	
11.72	78	14.30	1228	N	
10.50	78	14.30	1228	F	5.9
11.84	83	14.30	1186	N	
9.96	80	14.29	1183	N	
11.79	78	14.30	1180	N	
11.66	80	19.81	1178	N	
10.94	74	20.06	1237	F	5.6
11.24	80	19.93	1188	F	5.8
10.95	77	20.01	1131	N	
10.81	75	19.93	1140	N	
10.88	75	20.05	1144	N	
83282, LOCATION 3					
11.10	98	14.29	1176	F	2.4
10.27	95	14.29	1145	N	
11.06	88	14.29	1127	N	
11.10	86	14.29	1133	N	
11.17	85	19.77	1133	F	2.2
11.10	87	19.91	1089	F	3.6
11.11	87	19.87	1043	F	3
11.06	87	19.91	988	F	2.3
10.96	86	19.89	938	F	1.9
10.92	85	19.91	891	F	2.3
10.91	85	19.82	835	F	2.3
10.83	83	19.85	780	N	
10.69	81	19.71	791	N	
10.82	81	20.54	796	N	
83282 SPRAY FROM DOWNSTREAM					
11.31	94	14.29	1196	F	5.9
11.38	86	14.29	1139	N	
10.79	83	14.29	1133	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
11.11	81	14.29	1136	N	
11.30	83	19.94	1137	F	5.7
11.07	81	20.03	1090	F	5.9
11.03	82	20.00	1042	F	6.2
10.99	82	19.92	991	F	6.2
10.94	84	19.98	943	F	5.9
11.06	85	19.87	893	F	6.3
10.95	84	19.88	833	N	
11.11	80	19.94	824	F	6.4
11.08	81	19.87	780	N	
11.27	78	19.79	790	N	
11.38	77	20.00	793	N	
11.25	77	19.93	794	N	

HIGH REALISM TEST ARTICLE
83282 SPRAY FROM DOWNSTREAM, NO BLEED AIR FLOW; 4/27/88
VENTILATION AIR TEMPERATURE EFFECT ON MHSI

2.08	593	14.25	480	F	2.6
1.96	560	14.25	453	F	3.9
1.90	538	14.25	434	F	5.9
2.01	531	14.25	433	F	6.8
1.96	510	14.25	412	F	---
1.95	486	14.25	393	N	
1.99	482	14.25	386	N	
2.00	483	14.26	383	N	

83282, 7808, 5606 STREAM AT LOCATION 3;
83282, 7808, 5606, JP-4, JP-8 SPRAY FROM DOWNSTREAM;
JP-4, JP-8 STREAM AT LOCATION 5;
BAFFLE TESTS 4/28/88

83282 SPRAY FROM DOWNSTREAM

10.62	223	14.37	999	N	
11.34	255	14.37	1105	N	
14.15	310	14.40	1210	F	3.3
11.41	339	14.36	1161	F	4.4
12.80	359	14.37	1107	N	
13.66	360	14.38	1099	F	6.4
9.93	361	14.35	1053	N	
12.27	362	14.37	1048	N	
12.36	376	14.36	1048	N	

83282, LOCATION 3

11.60	364	14.35	1188	F	1.8

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
10.15	366	14.35	1159	F	1.3
11.98	370	14.36	1105	F	1.9
12.64	385	14.37	1056	F	1.2
10.53	381	14.35	1003	F	4.2
11.67	385	14.36	953	F	2.3
11.83	404	14.36	904	F	2
10.21	379	14.35	849	F	2
11.94	370	14.36	797	F	2.3
11.57	351	14.36	755	F	4
10.27	335	14.35	703	N	
10.68	340	14.36	698	N	
10.45	338	14.35	699	N	
7808, LOCATION 3					
13.05	247	14.41	1299	F	1.6
10.26	272	14.38	1263	F	1.9
11.74	289	14.40	1208	F	2.5
10.87	274	14.39	1159	N	
11.91	311	14.40	1152	N	
13.22	314	14.40	1151	F	2.4
10.26	315	14.37	1110	N	
12.43	336	14.40	1099	N	
13.69	359	14.40	1097	N	
7808 SPRAY FROM DOWNSTREAM					
12.46	302	14.40	1310	F	0.6
11.23	338	14.38	1259	F	0.8
11.30	337	14.38	1202	F	5.7
10.02	375	14.36	1142	N	
12.17	375	14.39	1147	N	
12.23	373	14.39	1151	N	
5606, LOCATION 3					
11.15	254	14.40	1207	F	2.6
11.77	272	14.39	1158	F	3.4
12.43	288	14.40	1106	F	3.3
11.61	299	14.39	1054	F	2.3
12.46	324	14.40	995	F	2.8
11.84	336	14.39	951	F	3.9
11.76	310	14.39	901	F	6
10.97	302	14.38	855	F	3.2
11.49	283	14.39	800	F	2.9
10.61	263	14.39	755	F	5.2
10.88	250	14.39	702	F	14.4
8.78	237	14.37	652	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
9.47	239	14.38	639	N	
11.84	248	14.40	645	N	
5606 SPRAY FROM DOWNSTREAM					
13.06	271	14.41	1197	N	
12.40	309	14.40	1304	F	3.7
11.63	306	14.39	1257	F	3.3
13.33	338	14.40	1201	F	4.5
11.10	330	14.38	1151	N	
10.65	326	14.38	1148	N	
11.57	336	14.38	1152	N	
JP-4, LOCATION 5					
13.20	301	14.40	1341	F	6.7
13.77	306	14.41	1306	F	6.9
11.32	331	14.38	1257	F	8
12.31	362	14.39	1206	N	
12.31	362	14.39	1196	N	
11.59	336	14.38	1199	N	
JP-4 SPRAY FROM DOWNSTREAM					
14.91	357	14.41	1356	F	0.9
11.70	336	14.39	1306	F	1.5
11.59	351	14.38	1244	F	2.2
12.46	412	14.39	1197	F	5.9
11.57	405	14.38	1153	F	5.7
12.13	398	14.38	1105	N	
12.41	404	14.38	1099	N	
11.81	427	14.38	1097	F	6.5
12.55	414	14.38	1056	N	
13.55	419	14.39	1049	N	
11.71	435	14.37	1047	N	
JP-8, LOCATION 5					
13.19	270	14.41	1300	F	3.1
10.73	253	14.39	1255	F	4.3
13.34	285	14.41	1204	F	4.9
13.60	326	14.41	1157	N	
11.07	336	14.39	1146	N	
12.11	374	14.38	1130	N	
JP-8 SPRAY FROM DOWNSTREAM					
12.36	273	14.40	1260	F	2.2
10.62	108	14.38	1198	N	
10.94	98	14.38	1191	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
9.38	98	14.37	1193	N	

HIGH REALISM TEST ARTICLE
JP-4, JP-8 STREAM AT LOCATION 5, 4/29/88

JP-8, LOCATION 5

0.00	131	14.36	1202	F	2.2
0.00	128	14.36	1151	N	
0.00	148	14.37	1140	N	
0.00	172	14.37	1157	F	3.1
0.00	133	14.37	1105	N	
0.00	163	14.37	1101	N	
0.00	183	14.38	1098	N	
1.08	144	14.37	1202	F	3.2
1.08	140	14.37	1151	F	4.3
1.07	133	14.37	1105	N	
1.14	168	14.37	1103	N	
1.18	191	14.37	1101	N	
2.09	132	14.36	1208	F	7.4
2.07	125	14.37	1154	F	12.3
2.08	131	14.36	1106	N	
2.22	166	14.37	1099	N	
2.19	185	14.37	1097	N	
4.04	127	14.37	1302	F	2.4
4.10	134	14.36	1258	F	2.4
4.07	125	14.36	1203	F	9.6
4.07	127	14.36	1152	N	
4.15	154	14.37	1149	N	
4.23	165	14.37	1148	N	
6.08	118	14.37	1252	F	7.9
6.09	126	14.36	1212	N	
6.31	148	14.37	1199	N	
6.14	157	14.36	1200	N	
8.13	119	14.38	1307	F	6.6
8.08	119	14.37	1261	F	8.3
7.99	116	14.37	1261	F	7.5
7.89	114	14.37	1211	N	
8.04	127	14.38	1203	N	
8.08	133	14.37	1199	N	

JP-4, LOCATION 5

0.00	151	14.35	1300	F	5
0.00	135	14.35	1248	F	7
0.00	137	14.35	1206	N	
0.00	169	14.35	1203	N	

VENT AIR VELOCITY (ft/sec)	VENT AIR TEMP (deg. F)	VENT AIR PRESS (psia)	DUCT TEMP (deg. F)	FIRE IGNITE? F = yes N = no	IGNITION DELAY (seconds after start of injection)
0.00	190	14.35	1201	N	
1.06	147	14.35	1302	F	2.5
1.05	143	14.35	1254	F	6.6
1.06	140	14.35	1204	F	9.2
1.05	134	14.35	1154	N	
1.11	168	14.35	1151	N	
1.13	189	14.35	1152	N	
1.99	127	14.35	1306	F	2.3
2.07	136	14.35	1255	F	9.3
2.06	136	14.35	1205	N	
2.15	173	14.35	1198	F	10.5
2.03	140	14.35	1155	N	
2.15	173	14.35	1148	N	
2.22	191	14.35	1148	N	
4.06	122	14.35	1306	F	3.8
4.06	122	14.35	1251	F	4.8
4.02	123	14.35	1204	N	
4.25	159	14.35	1197	N	
4.28	169	14.35	1200	N	
5.95	110	14.35	1306	N	
6.10	110	14.35	1360	F	6.9
6.08	119	14.34	1300	N	
6.22	151	14.35	1301	F	9.8
6.12	147	14.35	1262	F	11.9
6.33	168	14.35	1251	N	
6.47	184	14.35	1251	N	
6.10	199	14.35	1252	N	
8.15	137	14.35	1365	F	2.8
7.98	119	14.35	1309	N	
8.02	125	14.35	1306	F	11.3
8.19	124	14.35	1259	N	
8.10	130	14.35	1259	N	
8.08	130	14.35	1251	N	

APPENDIX B: Temperature Data Uncertainty Analysis

This Appendix is assembled from analyses that were performed following the completion of the hot surface ignition testing. It Contains the following:

1.) Error Accumulation ROM Estimate

TEMPERATURE	900°F		1400°F	
	ERROR	$(ERROR)^2$	ERROR	$(ERROR)^2$
T/C WIRE (Special grade)	±3.6	12.96	5.6	31.26
EXTENSION WIRE (Assumed std. wire)	±4.0	16.00	4.0	16.00
REFERENCE JUNCTION (Electrical MV insertion type assumed)	±0.2	0.04	0.2	0.04
MODCOMP AIS (Based on MV insertion data provided)	±1.8	3.24	2.25	5.06
TABLE LOOK UP (Worst case assumed)	±0.2	0.04	0.2	0.04
TOTALS	±9.8	32.28	12.25	52.5

$\sqrt{\varepsilon^2 + \varepsilon^2 + \cdots} =$	± 5.68	±7.25
ADD KNOWN AIS BIAS FACTOR	+15.18°F	+24.85°F
	+ 3.82°F	+10.35°F

This represents a ROM estimate of potentially significant error sources in the temperature measurements system. Numbers are based on standard industry information or typical numbers from past similar work.

COORDINATION SHEET

TO: A.M. Johnson 33-14 L8347-088-RJC-057

CC: J.L. Howard 86-12 July 28, 1988
A.L. da Costa 33-18

SUBJECT: Determination of the Intrinsic Thermocouple Measurement Error for the Hot Service Ignition Test

REFERENCES

[1] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Company, 1980

[2] D.R. Pitts and L.E. Sissom, Heat Transfer, Schaums Outline Series, McGraw-Hill Book Company, 1977

SUMMARY

An analysis of an intrinsic thermocouple installation for the hot service ignition test was done to determine the error between the actual surface temperature of the bleed air duct and the temperature measured by the thermocouple. Results show that for a wide range of conditions during the test a maximum error of approximately -27 F could be expected, for surface temperatures in the range of 450 to 1350 F. Note that the error produces a lower thermocouple reading than the actual surface temperature of the duct, due to the fin effect of the thermocouple leads. The minimum error for the range of test conditions was -9 F. For the test conditions where the air temperature within the enclosure was greater than the bleed duct temperature the thermocouple created a positive error in the reading.

INTRODUCTION

A set of tests had been completed in order to determine the ignition conditions for a variety of fuels and lubricants in a simulated engine compartment. As part of the post data analysis for the test, an analysis of the "fin effect" error of the thermocouple leads has been completed. When a thermocouple is used to measure the surface temperature of an object, it will inherently change the surface temperature at the point of measurement, due to its presence. This error is due to the convective and radiative heat losses of the thermocouple leads to the surrounding air flow and walls and hence, its action as a fin attached to the surface.

A wide range of air temperature and flow velocities were present during the tests and it is required that an error correction be estimated for the surface temperature measurement due to this fin effect error. The bleed air duct is made of Inconel 625 and the thermocouples were a type K (chromel/alumel), 24 AWG and insulated with a fiberglass braid.

MODEL DESCRIPTION

The thermal math model used to determine the thermocouple error consisted of a steady-state thermal network model of a 12 inch section of the bleed duct and one of the thermocouples attached to it. The thermocouple lead length was set at about 6 inches, which was the length exposed to the air flow in the enclosure. The solution technique for the thermal network is based on the presentation in [1]. The thermal math model consisted of 36 nodes for the bleed air duct, 11 nodes for the thermocouple and 3 boundary nodes, see Figure 1. One boundary node represented the temperature of the air flow through the bleed air duct, while the other two represented the air flow through the enclosure and the enclosure surface temperature. These boundary values (see Tables 1 and 2 in results) were taken from the test conditions recorded during the test.

The correlations used for the forced convection air flow over the bleed air duct and the air flow inside the bleed air duct can be found in [2]. For flow over the duct and leads the correlation used was for cross flow over a cylinder,

$$Nu = CPr^{1/3}Re^{n}$$

Where,

- Nu - The Nusselt number
- Re - The Reynolds number, VD/v
- Pr - The Prandtl number, v/k
- V - Fluid flow velocity
- D - Characteristic length, outside diameter of the cylinder
- k - Thermal conductivity
- v - kinematic viscosity

The constants are given by the range of the Reynolds number,

Re	C	n
0.4 to 4	0.989	0.330
4 to 40	0.911	0.385
40 to 4,000	0.683	0.466
4,000 to 40,000	0.193	0.618
40,000 to 400,000	0.0266	0.805

Then the heat transfer coefficient is given by,

$$h = Nu*k/D$$

For the forced convection on the inside of the bleed air duct the following correlation was used,

$$Nu = (0.023)Re^{0.8}P_r^{1/3}$$

Where the characteristic length is the inside diameter of the duct. The heat transfer coefficient is determined as shown above.

The radiation heat transfer to the enclosure was assumed to be from a gray body, the outside of the duct and the thermocouple leads, to a black enclosure. The enclosure was reported to be covered with a coating of soot from the testing and hence its emissivity should be close to 1.0. The emissivity of the bleed air duct and thermocouple leads was assumed to be 0.80 for this analysis.

The thermal properties for the model were fixed at,

	Thermal Conductivity (Btu/hr-ft-F)
Inconel 625	10.0
Chromel	10.0
Alumel	10.0
Fiberglass Tape	0.1

Note that the chromel and alumel are estimated values at this time. It is expected that the thermal conductivity for these two materials will be very close to the values used. The air velocity in the bleed duct was calculated using a mass flow rate of 1.0 lbm/sec at a pressure of 130 psia and the given temperature of the test condition.

RESULTS

Results are presented for a total of 3 basic sets of conditions that were run in the test section. These sets of conditions were chosen to represent the minimum and maximum errors expected for the test configurations that were run. Table 1 shows the results for the lowest enclosure air temperature, over a range of flow velocities and bleed air duct temperatures. The maximum error occurs for the highest difference between bleed duct temperature and the enclosure air temperature, as would be expected. Note that the enclosure wall temperature is expected to be lower than the air temperature, due to losses to the surrounding environment.

Table 2 contains the results for the elevated enclosure air temperature cases. This also resulted in the enclosure wall temperatures to be higher. Only the extreme enclosure air velocities (minimum and maximum) were run for these cases. As would be expected the errors in the thermocouple readings are lower than the cases for which the temperature difference between the bleed duct and enclosure are higher. It is interesting to note that for case 3a, in which the air temperature in the enclosure exceeds the bleed duct air temperature, that the effect of the thermocouple was to locally heat the duct. This condition gave the lowest predicted error in the thermocouple reading.

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Attachments:

1.) Figure B-1. Modeled Section of Bleed Duct with Thermocouples

2.) Table B-1. Uncertainty Analysis for Ambient Air Temperature Tests

3.) Table B-2. Uncertainty Analysis for Elevated Air Temperature Tests

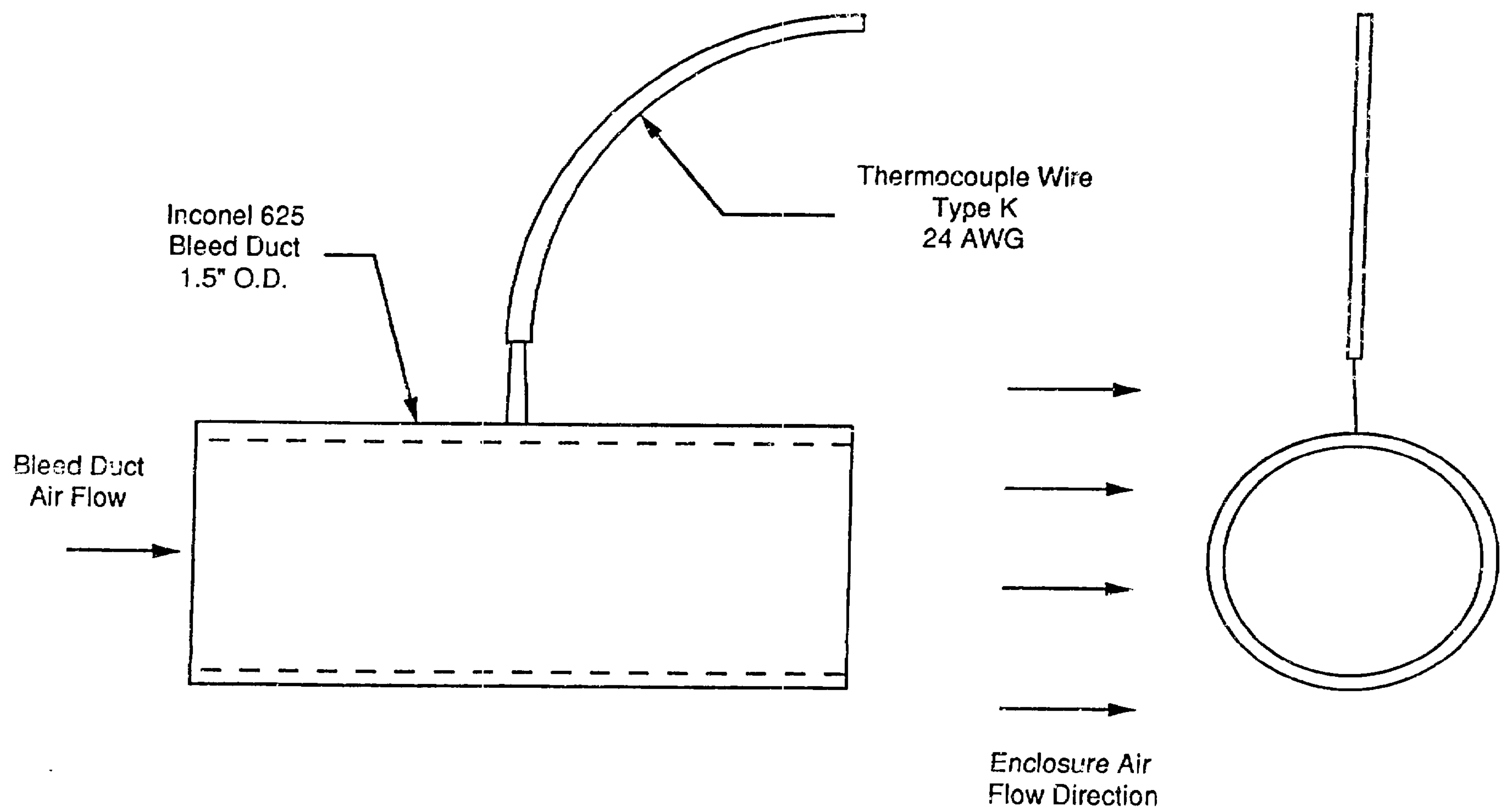


Figure B–1. Modeled Section of Bleed Duct with Thermocouples

Table B-1. Uncertainty Analysis for Ambient Air Temperature Tests

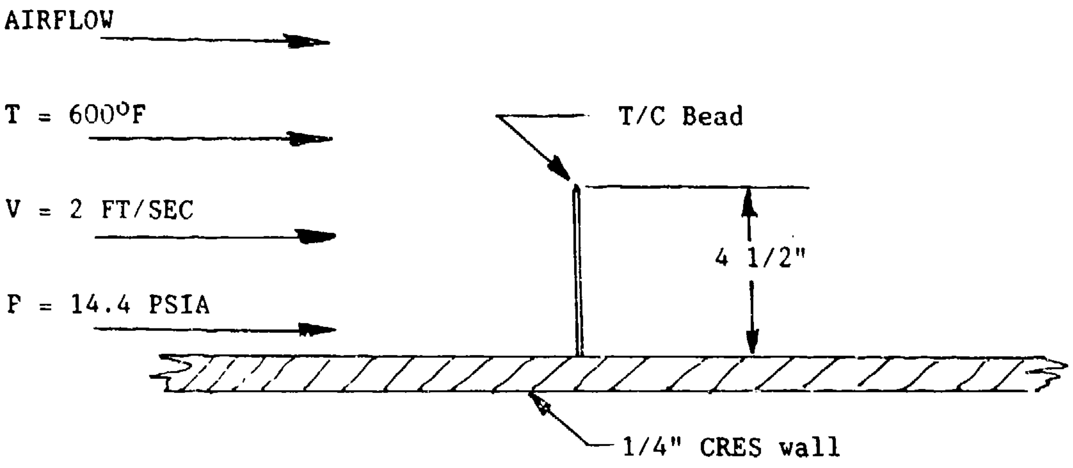
	Case Number			
	1a	1b	1c	1d
Air Temperature (F)	120.0	120.0	120.0	120.0
Enclosure Wall Temperature (F)	110.0	110.0	110.0	110.0
Enclosure Air Velocity (ft/sec)	0.25	2.0	11.0	20.0
Enclosure Pressure (psia)	14.7	14.7	14.7	14.7
Bleed Duct Temperature (F)	800.0	500.0	1350.0	1600.0
Bleed Duct Air Velocity (ft/sec)	322.0	245.0	462.0	526.0
Bleed Duct Pressure (psia)	130.0	130.0	130.0	130.0
Duct Surface Temperature (F)	704.0	446.0	1010.0	1119.0
Thermocouple Temperature (F)	686.0	434.0	985.0	1092.0
Calculated Error (Ttc - Tsurf) (F)	-18.0	-12.0	-25.0	-27.0

Table B-2. Uncertainty Analysis for Elevated Air Temperature Tests

	Case Number 2a	2b	3a	3b
Air Temperature (F)	300.0	300.0	600.0	600.0
Enclosure Wall Temperature (F)	200.0	200.0	350.0	350.0
Enclosure Air Velocity (ft/sec)	0.25	20.0	0.25	20.0
Enclosure Pressure (psia)	14.7	14.7	14.7	14.7
Bleed Duct Temperature (F)	600.0	1350.0	500.0	1350.0
Bleed Duct Air Velocity (ft/sec)	271.0	462.0	245.0	462.0
Bleed Duct Pressure (psia)	130.0	130.0	130.0	130.0
Duct Surface Temperature (F)	551.0	1002.0	485.0	1053.0
Thermocouple Temperature (F)	542.0	982.0	487.0	1039.0
Calculated Error (Ttc - Tsurf) (F)	-9.0	-20.0	2.0	-14.0

3.) Extrapolation of Error Analysis to AENFTS Air Temperature Thermocouples

for the following test conditions



Various wall temperatures from 100°F to 500°F

If we assume that the conduction loss down the lead is negligable, then we have:

Radiation Heat Transer = Convective Heat Transfer

or

$$A_{tc}\sigma\epsilon_{tc}\,(T_{tc}^{4} - T_{wall}^{4}) = A_{tc}\,h\,(T_{air} - T_{tc})$$

where it has been assumed that the shape factor between the bead and the wall is equal to 1.0, and:

σ = Stefan-Boltzmann Constant
0.1713 X 10^{-8} Btu/hr-ft^2 - °R^4

ϵ_{tc} = emissivity of the thermocouple

h = heat transfer coefficient between the thermocouple bead and the airflow this leads to:

$$(T_{tc}^4 - T_{wall}^4) = \frac{h}{\sigma \epsilon_{tc}} (T_{air} - T_{tc})$$

Then, for a given T_{air} and T_{wall}, this must be solved for T_{tc}.

and:

$\epsilon_{tc} = 0.8$, which is the usual assumption for an unknown material

$$h = \frac{N_u k}{D}$$

N_u = Nusselt Number

k = thermal conductivity

D = characteristic length

and $N_u = 0.37 R_e^{0.6}$ for a gas flow over a sphere (the T/C bead)

and

$$R_e = \frac{U D}{v}$$

then
$U = 1$ ft/sec
$D = 0.125'' = 0.0104'$
$v = 40.8 \times 10^{-5}$ ft^2/sec (440°F)
$k = 0.02333$ Btu/hr-ft-°F (440°F)

$$R_e = \frac{(1 \text{ ft/sec})(0.0104 \text{ ft})}{40.80 \times 10^{-5} \text{ ft}^2/\text{sec}} = 25.5$$

$$Nu = 0.27\ (25.5)^{0.6} = 2.6$$

$$h = \frac{(2.6)(0.02333 \text{ Btu/hr-ft-°F})}{(0.0104 \text{ ft})} = 5.8 \text{ Btu/hr-ft-°F}$$

Hence for 600°F air at 2 ft/sec and 14.4 psia:

Thermocouple indicated temperature and error for a given wall temperature are tabulated below based on the preceeding approach and assumptions:

T_{wall} ($^{\circ}$F)	T_{tc} ($^{\circ}$F)	T/C error ($^{\circ}$F)
100	457	143
200	469	131
300	488	112
400	515	85
500	552	48

Similar analysis for 480°F air at 2 ft/sec and 14.4 psia and a wall temperature of 423°F:

T_{wall} ($^{\circ}$F)	T_{tc} ($^{\circ}$F)	T/C error ($^{\circ}$F)
423	457	23

Finally, when it was established that 83282 was igniting in air with an indicated temperature of 510°F, with a wall temperature observed to be 425°F, extrapolation between these two tables allowed estimation of the air temperature measurement error in this case to be 60°F.

APPENDIX C. PERTINENT AIRCRAFT FLUID PROPERTIES

Properties are needed for the five aircraft fluids of interest (JP-4, JP-8, 5606, 83282 and 7808) to carry out calculations on the basis of which one can interpret the test results. The properties of interest include:

- o basic properties such as molecular weight and vapor pressures

- o thermophysical properties such as surface tension, viscosity, and thermal conductivity

- o kinetic properties for the ignition reactions

- o boiling heat transfer coefficients

Most of these properties (except for the heat transfer coefficients) were readily available for JP-4 and JP-8. However, they were not readily available for the heavier fluids (5606, 83282 and 7808) because:

- each of the above fluid designations represent a family of fluids that satisfy military specifications. For example, 5606 consists of a heavy kerosene as a base stock, thickened with additives. Also, properties will vary for different petroleum base stocks.

- these properties are not specified in military specs (unlike viscosity, lubricity, thermal stability, etc.)

- little modeling effort has been devoted to these fluids in the past (unlike the case of the JP fuels)

To obtain even rough values or estimates for such properties, three approaches were followed:

- a manual search of the MIT and the AFWAL library including the MIL standards

- a computerized search of 4 databases: NTIS, Compendex, NASA and Chem Abstracts.

- telephone calls and selected meetings with key researches in the field and a supplier of these fluids.

A summary of the found thermophysical properties is given in Table C-1.

Kinetic data for the ignition reaction were found in the literature for JP-4 and JP-8 (Ref. C-1), but not for the other fluids. They are given in Table C-1. We recommend that such basic data be measure in future work.

Vapor Pressure Data

We collected vapor pressure (P_{vap}) data at various saturation temperatures (T_{sat}) from a variety of sources. The data are shown in an Arhenius plot in Figure C-1. Note that the relationship between log P_{vap} and the inverse absolute temperature T_{sat} is linear except at high temperature for 83828 and 5606. This is not surprising for these multicomponent fluids.

We used the Clayperon equation to calculate the latent heat of vaporization (H_{fg}) from the vapor pressure data:

$$H_{fg} = \frac{R \cdot T_{sat}^2}{M.W. \cdot P_{vap}} \cdot \frac{dP_{vap}}{dT_{sat}}$$

where,

R = Universal gas constant

M.W.= Molecular weight

Table C-1. Fluid Properties Used in Calculations

PROPERTIES	JP-4	JP-8	5606	83282	7808
Molecular Weight, kg/kmole	125	166	266	400	425
Avg. Latent Heat*, H_{fg}, kJ/kg	211	229	204	105	357
Effective Saturation Temperature*, ^{o}F					
at 20 psia	236	405	496	865	570
at 14.4 psia	209	376	470	805	559
at 10 psia	182	346	444	744	548
at 5.5 psia	141	302	403	656	529
<u>LIQUIDS AT 20^{o}C</u> (from various sources)					
Specific Gravity	0.76	0.81	0.88	0.85	0.95
Absolute Viscosity, g/cm·s	0.0081	0.013	1.15	4.57	2.30
Kinematic Viscosity, mm·sq/s	0.95	1.65	131	536	242
Surface Tension, dyne/cm	21.[illegible]	23.3	31.5	30	30
Specific Heat, kJ/kg^{o}K	2.06	1.95	2.19	2.19	2.19
Thermal Conductivity, W/m^{o}K	0.115	0.115	0.115	0.115	0.115
Autoignition Temperature, ^{o}F	447-475	460	435	650	735
<u>SATURATED VAPORS</u> (taken as air at various temperatures)					
Absolute viscosity#, gm/cm·s	2.4E-04	2.4E-04	2.4E-04	2.4E-04	2.4E-04
Thermal Conductivity#, W/m^{o}K	0.03	0.03	0.03	0.03	0.03
<u>KINETICS OF OVERALL IGNITION REACTIONS</u> (from Reference C-1)	JP-4	JP-8			
Pre-exponential Fact, ms/atm^{2}	1.17E-09	1.68E-08			
Activation Energy, kcal/mole^{o}K	43.1	37.8			
Order of Reaction	2	2			

* = estimated based on vapor pressure data

\# = at 100^{o}C

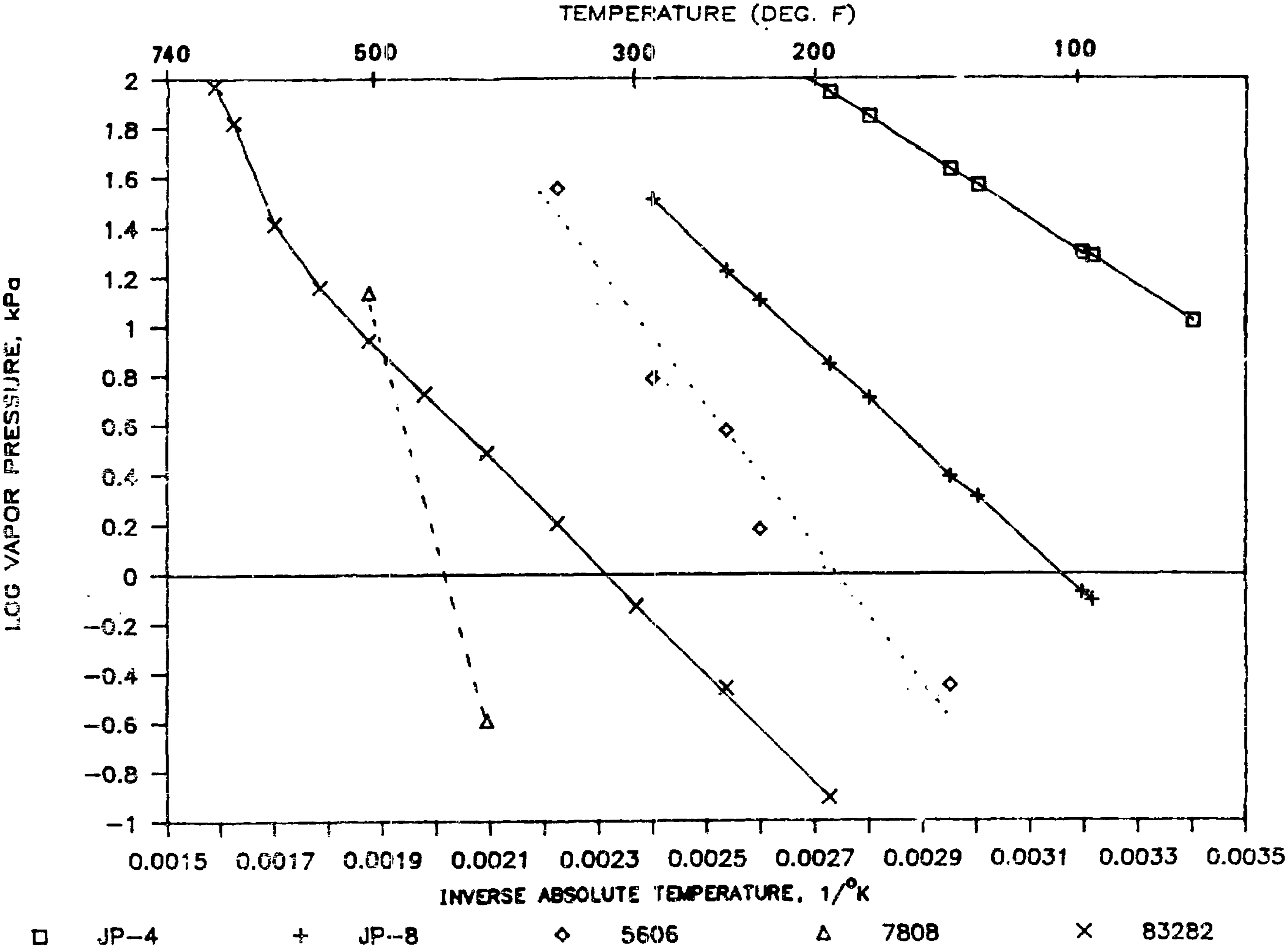


Figure C-1. Relative Volatility of Aircraft Fluids

We calculated the slope of the log P_{vap}-Inverse Absolute T_{sat} relationship (Fig. C-1) at various temperatures and averaged the values (for simplicity). Also, we used reasonable average molecular weights for these multicomponent fluids as given in Table C-1. Thus, we calculated an estimate for an average latent heat of each fluid as given in Table C-1.

It should be noted that our data collection/analysis was very rough. For example, we found only two data points for the vapor pressure of 7808. Although, the results are adequate for our proposes, we recommend that effort be devoted in the future to further collect and document fluid property data.

REFERENCES

C-1. Spadaccini, L. J. and J. A. TeVelde, "Autoignition Characteristics of Aircraft-type Fluids", NASA CR-159886, June 1980.

APPENDIX D. SPRAY ANALYSIS

In the spray tests, liquid flows at high velocity from the nozzle. The liquid breaks up into droplets that decelerate, heat up and evaporate as they approach the duct. The vapors, mix with air, heat up further and ignition occurs when the appropriate temperature-composition-time are attained.

In this Appendix, we present a simplified classical analysis for these key processes in spray ignition, adapted to the conditions of the simple duct tests in this study. Our objective is to determine characteristics times and relative importance of various processes that can help us interpret the results (and not to develop any extensive mathematical models). For simplicity, each key process is treated separately. The results are then combined as appropriate.

We discuss below these key processes along with their governing equations. The key processes are:

- o atomization
- o droplet dynamics
- o droplet heating/evaporation in duct boundary layer
- o chemical kinetics
- o ignition criterion
- o droplet impingement and heating at duct surface

Atomization

Consider the atomization of a fluid through a pressurized nozzle into stagnant air. As the liquid exits the nozzle, it acquires a high velocity. The liquid surface becomes unstable and breaks up into ligaments and eventually into droplets. From dimensional reasoning, one expects the resulting average droplet diameter (d_a) to be given by:

$$d_a/D_n = \text{function } (Re_n , We_n)$$

where, D_n = nozzle diameter

Re_n = Reynolds number at nozzle exit

We_n = Weber number at nozzle exit

Correlations have been proposed by various investigators for pressure atomization (Refs. D-1 and D-2) such as:

$$d_{32} = 150{,}000 \cdot D_n^{1/2} \cdot \Delta P^{-3/8} \cdot \sigma_1^{1/4} \cdot \mu_1^{1/4} \cdot \rho_1^{-1/8} \cdot \rho_a^{-1/5}$$

where: d_{32} = Volume to surface mean diameter, micron

ΔP = Pressure across nozzle, dyne/cm^2

σ_1 = Liquid surface tension, dyne/cm

μ_1 = Liquid density, g/cm^3

ρ_1 = Liquid absolute viscosity, g/cm·s

ρ_a = Air density, g/cm^3

Droplet Dynamics

Consider a droplet of initial diameter (d_i) propelled with an initial velocity of (V_i) into a moving gas stream with a gas velocity (V_g). The gas stream is the ventilation air. It exerts a drag force on the droplet that decelerates it.

The conditions of spray injection, the droplet Reynolds numbers (Re_d) is of the order of 10 to 1000. For this range of Re, the drag coefficient (C_d)) of the droplet was obtained (within $\pm$30%) by curve fitting the data of McAdams with the following expression:

$$C_d = 13 / (Re_d)^{1/2}$$

where: Re_d = Reynolds number based on d_i and the droplet local velocity relative to the gas (V_i - V_g)

A force balance on the droplet yields the instantaneous droplet velocity (V) and its trajectory (x) as a function of time (t):

$$V/V_i = 1/(1 + 0.5\,\beta\sqrt{V_i} \cdot t)^2$$

where $\beta = 9.8\ (\rho_g \cdot \mu_g)^{1/2} / (\rho_l \cdot d^{3/2})$

= velocity decay parameter

ρ_l, ρ_g = densities of liquid and gas, respectively

μ_g = gas viscosity at the ventilation air temperature

and $x/(x_d - x) = 0.5\sqrt{V_i} \cdot \beta \cdot t$ for t < time to impact

where $x_d = 0.5\sqrt{V_i}/\beta$

= deceleration distance required for V to decay to V_g

If x_d is greater than the spacing between the nozzle and the duct, the trajectory equation above yields directly the time to impact with the duct; otherwise, first V decays to V_g according to the above equations, and then, the droplet moves with the gas stream at V_g until impact with the duct.

The transit time near the duct (t_t) is obtained by dividing a heating length by the droplet velocity at the duct leading edge. For the simple duct experiments, the heating length is assumed to be the duct diameter (1.5 inches). For the high realism tests, the heating length is taken to be 22.5 inches (roughly the projected length of the hot duct along the spray direction).

Droplet Heating/Evaporation in a Hot Stream

The results of the above analysis are used as initial conditions for the droplet heating/evaporation analysis.

Consider a spherical droplet of fuel at an initial temperature (T_o), engulfed in a hot air stream at a higher temperature (T_h). The hot air is in the boundary layer of the duct. The relative velocity between droplet and air is governed by the droplet initial velocity and by drag from the much slower ventilation air.

The heat transfer from the air to the droplet is given by the Nusselt number (N_u) as follows:

$$N_u = 2 + 0.6 \, (Re_d)^{1/2} \cdot (Pr)^{1/3}$$

where
$N_u = h \cdot d/k$
d = instantaneous droplet diameter
h = heat transfer coefficient
k = thermal conductivity of air
Pr = Prandtl number = 0.7

and gas properties are taken at a mean temperature in the boundary layer.

The vapor mass flux ($\dot{m}''$) from the droplet surface due to heat/mass transfer is given by:

$$\dot{m}'' = N_u \cdot (k/d \cdot c_g) \cdot \ln (B + 1)$$

where
c_g = specific heat of air

B = mass transfer number = $c_g \cdot (T_h - T_b)/(H_{fg} + c_l \cdot (T_b - T_o))$

T_b = boiling point of liquid at ambient pressure

H_{fg} = latent heat of vaporization at T_b

c_l = specific heat of liquid

A mass balance on the droplet yields the droplet evaporation time (t_e) which is given by one of two equations depending on the flow field;

For nearly stagnant flow, $N_u = 2$ and:

$$t_e = d_i^2 \cdot \rho_l \cdot c_g/(8\ kg.\ln (B+1))$$

where d_i = initial droplet diameter

for forced convection flow,

$$t_e = 0.56\ d_i^2 \cdot \rho_e \cdot c_g/[kg \cdot (Re_d)^{1/2} \cdot (Pr)^{1/2} \ln (B+1)]$$

Kinetics of Ignition

Following Reference D-3, a one-step overall second order reaction was used to model the kinetic portion of the ignition delay time:

$$t_c = f \cdot \exp (E/RT) / P^n$$

where:
- t_c = induction time, ms
- f = pre-exponential factor, ms/atm^2
- E = activation energy, kcal/mole^oK
- P = pressure, atm
- R = universal gas constant
- T = absolute temperature, ^oK
- n = order of reaction

Ignition Criterion

Ignition is assumed to occur when the sum of the evaporation and chemical times is less than the transit time near the hot duct. The temperature is increased parametrically until this criteria is satisfied. This was done only for JP-4 and JP-8 for which we found kinetic data in the literature.

Droplet Impingement Against a Hot Surface

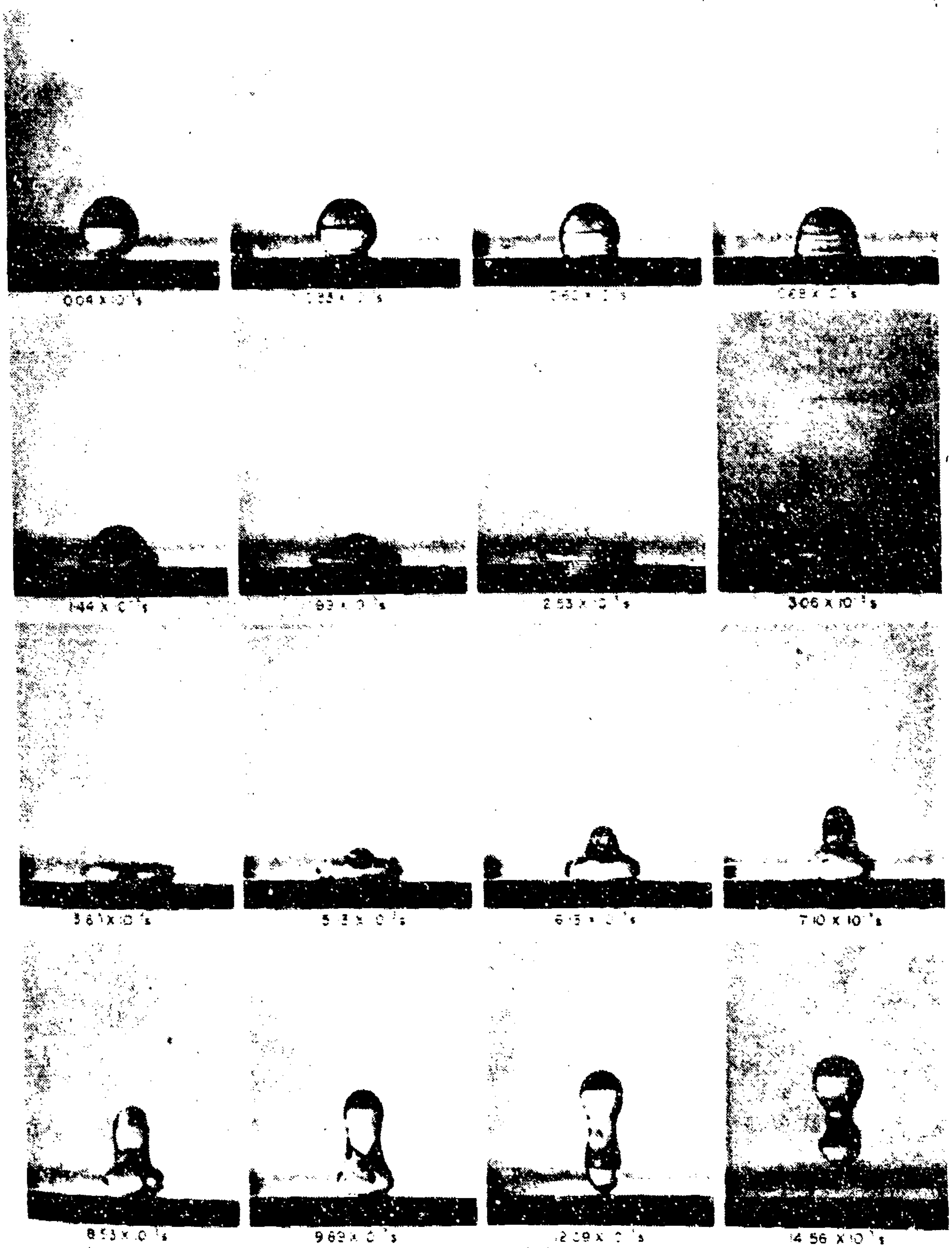
From the droplet dynamic analysis presented above, one predicts that small droplets decelerate before reaching the duct; are entrained by the ventilation air; and may flow around the duct in its hot boundary layer. On the other hand, large droplets will decelerate more slowly and impinge on the duct at high velocity and large Weber number. The dynamic of such an impingement and its effect on heat transfer from the surface to the droplet is a complicated process that is not completely understood.

Accordingly, from the literature we identified the types of reported behaviors and governing parameters that may be used in interpreting our test data. Key experimental results found for water are:

1. Effect of Weber Number (We): Figures D-1 and D-2 (from Ref. D-4) show the dynamic behavior as a function of time of a 2.3 mm water drop impacting a hot polished gold surface (at 400°C) at Weber Numbers of 15 and 148, (droplet velocity ≈ 0.7 and 4 m/s) respectively. (While these conditions are different from those of our tests, this study presented photographs that are quite revealing concerning the key processes.) Note that:

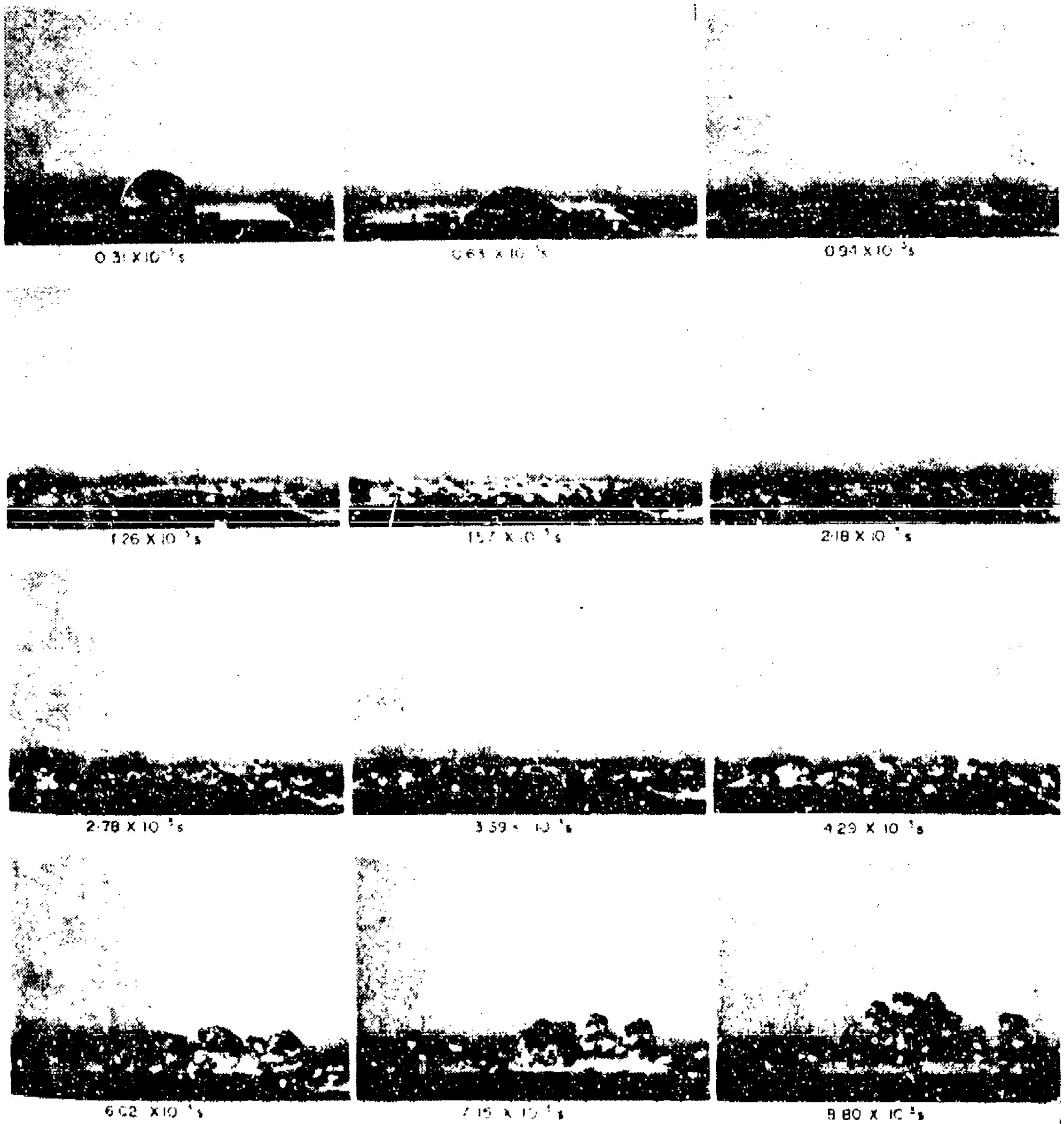
- at low We, the droplet spreads on the surface, then rebounds from the surface "intact" (at 15ms)

- at high We, it spreads, and disintegrates into a large number of smaller droplets as a fine spray (in 8.8 ms). Subsequent vaporization may now occur much more rapidly because of the smaller diameters of the droplets.



Course of the impact of a water drop on a hot polished gold surface (surface temperature 400°C, drop diameter 2·3 mm, We_{an} 15). Time is measured from the moment of initial contact.

Figure D–1. Effect of Weber Number on Boiling



Course of the impact of a water drop on a hot polished gold surface (surface temperature 400 C, drop diameter 2·3 mm, $We_{an} = 184$). Time is measured from the moment of initial contact.

Figure D–2. Effect of Weber Number on Boiling

2. Effect of surface temperature: Figure D-3 shows the water droplet impacting the same surface at 4 surface temperatures, and for 4 times (from impact) at each temperature. The droplet conditions were: diameter = 2.17 mm, velocity = 1.25 m/s, 30^{o} angle normal to the surface, We = 41, T = 20^{o}C. Note that the effect of increasing surface temperature (T_w) is highly nonlinear:

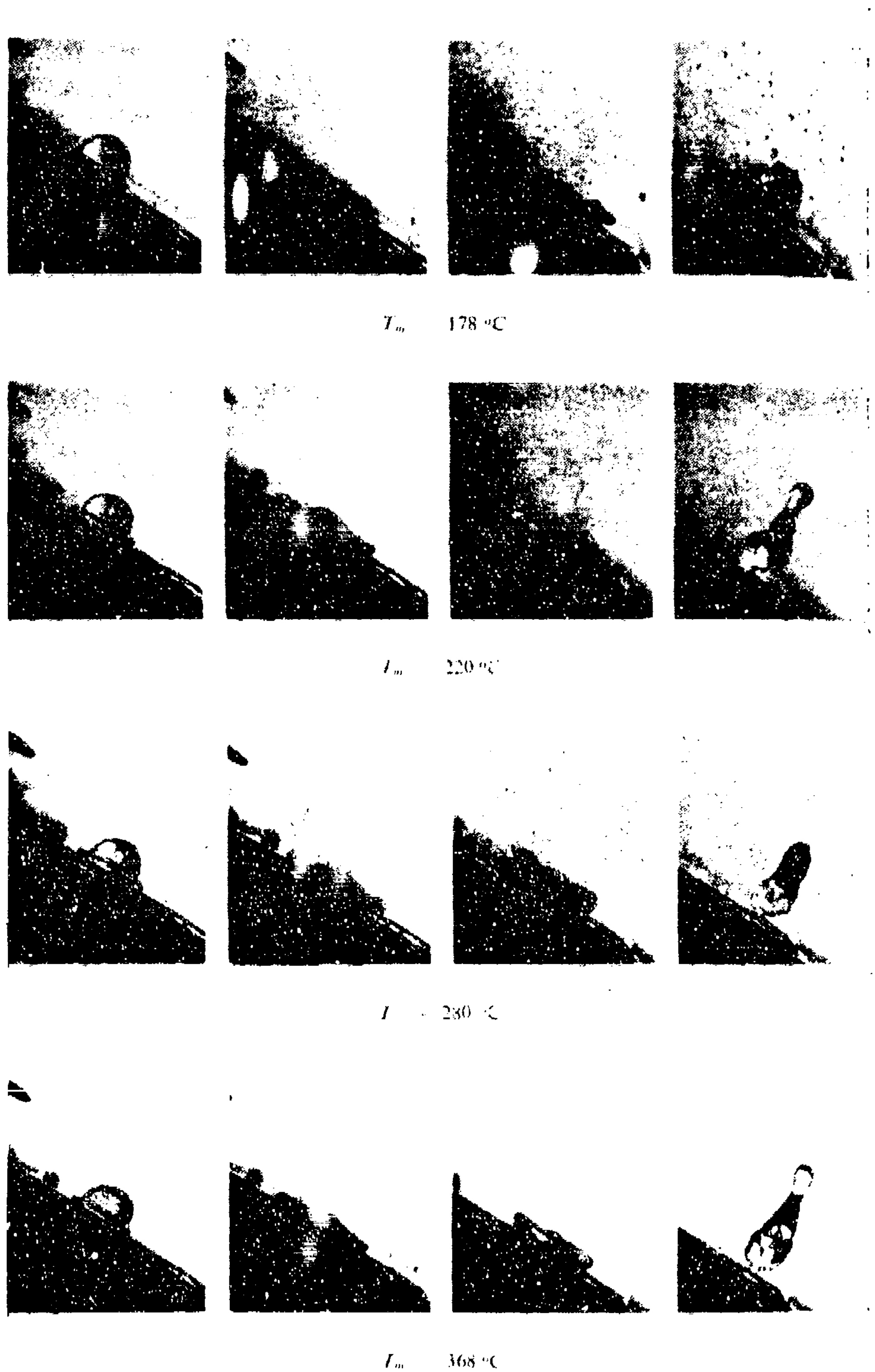
- up to about T_w = 200^{o}C (T_w - T_{sat} = 100^{o}C), the contact between liquid and vapor is such that a great deal of the vapor produced at the bottom of the drop is trapped by the liquid and breaks through during the collision. Thus, a spray is produced as shown for T = 178^{o}C.

- at about T_w = 220^{o}C (T_w - T_{sat} = 120^{o}C), the droplet behaves vary calmly with no spray formation.

- at T_w = 250^{o}C and above (T_w - T_{sat} > 150^{o}C), vapors are formed explosively inside the drop. When they rise and break out through the liquid, they produce a very fine spray.

- when T_w is increased to about 400^{o}C (T_w - T_{sat} = 300^{o}C), a vapor film is formed underneath the drop. No vapor bubbles were seen in the drop. The drop is said to have reached the fully spheroidal (or Leidenfrost) state.

Clearly, the boiling behavior depends on where vapor bubbles are formed and on whether or not they are trapped by the liquid film. We recommend that this subject be investigated in future work for the conditions of interest to hot surface ignition.



Course of the impact of a water drop of 20 °C upon a hot, polished gold surface (drop diameter 2·17 mm, v_a = 1·25 m/sec, ϵ = 30°, so that We_{an} = 41). The pictures are in all four cases taken at respectively 0·63, 1·88, 4·84, and 9·27 × 10^{-3} sec after initial contact.

Figure D–3. Effect of Weber Number on Boiling of Heated Fluid

REFERENCES:

D-1. Elkotb, M. M., "Fuel Atomization for Spray Modelling", Progress in Energy and Combustion Science, 1982, Vol. 8, pp. 61-91.

D-2. Dorman, British J. of Applied Physics, Vol. 3, June 52, p. 189.

D-3. Spadaccini, L. J. and J. A TeVelde, "Autoignition Characteristics of Aircraft-type Fluids", NASA CR-159886, June 1980.

D-4 Wachters, L. H. J. and N. A. J. Westerling, "The heat transfer from a hot wall to impinging water drops in the spheroidal state", Chemical Engineering Science, 1966, Vol. 21, pp. 1047-1056.

APPENDIX E. DETERMINATION OF BOILING REGIMES FOR HOT SURFACE IGNITION TESTS

In the stream tests, the fluid is injected by a drip tube onto a horizontal hot duct. The fluid jet impacts the duct and spreads as a thin film outwardly from the impact point in all radial directions. This liquid flow produces a stagnation-like flow field. After a very short distance, the spreading fluid breaks up into rivulets. This distance depends on a number of variables and is of the order of 0.3 inch based on photographs obtained in a similar experiment. The rivulets continue to flow over the duct and further break up into ligaments and droplets (See Plate E-1).

A key unknown in this study is whether boiling occurs in the nucleate or film boiling regime. Depending on the regime, large differences are expected in the rates of fluid evaporation and the attained temperatures--which in turn would affect the ignition results in this study. Identification of the boiling regime was deemed needed to help interpret the results.

We searched the literature for data on boiling behaviors of aircraft fluids of interest. We found no directly pertinent data under either the above configuration or the simpler case of a boiling liquid pool. We set out to determine the boiling regimes for the test conditions of this study using standard correlations from the literature. The results are presented in the Appendix.

Boiling Heat Transfer Correlations

In boiling, the driving force for heat transfer is the excess wall temperature (T_W) over the saturation temperature (T_{sat}) of the liquid. Thus. the heat transfer coefficient (h) in boiling is usually defined as :

$$h = (q/A) / (T_W - T_{sat})$$

Plate E-1. 5606 hydraulic Fluid Streamed onto Hot Horizontal Manifold Test Rig

Photo acquired during experiment performed on Monsanto test apparatus (Federal Test Method Standard No. 791B, Method 6053, 15 Jan, 69) installed at WPAFB.

Correlations for h are given in the literature (Ref. E-1) for static, pool boiling of single-component pure substances. For simplicity, we applied these correlations to our flowing, multi-component fluids using the collected thermophysical properties and estimated "average" thermodynamic properties from Appendix C. Also, we simplified these correlations to the case where the ratio of vapor density (ρ_v) to liquid density (ρ_l) is much less than unity. Such a case applies to the conditions of this study.

These simplified correlations are presented below:

Nucleate boiling

In this regime, bubbles form (nucleation), grow and move away from the surface. Their motion stirs the liquid near the hot surface and produces very high heat transfer coefficients (h_n). The dependence of h_n on the excess temperature is give by:

$$h_n = h_{n,max} \left(\frac{(T_w - T_{sat})}{(T_w - T_{sat})_{max}} \right)^2$$

Unfortunately, Reference E-1 did not define $(T_w - T_{sat})_{max}$. Therefore, we assume (based on the shape of boiling curves for a variety of fluids) that:

$$(T_w - T_{sat})_{max} = 0.3\ (T_w - T_{sat})_{min}$$

where $(T_w - T_{sat})_{min}$ is defined in the next section.

$h_{n,max}$ was obtained from the equation given in Reference E-1 for the maximum (or burnout) heat flux in the nucleate boiling regime $(q/A)_{n,max}$ as:

$$(q/A)_{n,max} = 143 \cdot H_{fg} \cdot \rho_v \left(\frac{\rho_l}{\rho_v} \right)^{0.6}$$

Film Boiling Regime

In film boiling, the vapor generated at the liquid-vapor interface produces a vapor film that separates the liquid from the hot surface. Heat is transferred by conduction and radiation across the vapor film. For the case of liquid droplets (as in a spray), the droplets will dance around the surface, and the phenomenon is referred to as "Leidenfrost".

The film boiling regime starts at a specific value of excess wall temperature over saturation temperature given as:

$$(T_w - T_{sat})_{min} = 0.127 \frac{(g)^{1/3} H_{fg} \cdot \rho_v}{k_{vf}} \left(\frac{\sigma}{\rho_l}\right)^{1/2} \left(\frac{\mu_{vf}}{\rho_l}\right)^{1/3}$$

where: g = acceleration of gravity, ft/hr^2

k_{vf} = thermal conductivity of vapor in the film between the wall and liquid, Btu/hr.ft·°F

σ = surface tension of liquid, lbf/ft

μ_{vf} = viscosity of the vapor in the film between wall and liquid, lbm/hr·ft

The heat transfer coefficient (h_f) in this regime is given by:

$$h_f = 0.425(g)^{1/4} \left\{ \frac{k_{vf}^3 \cdot H_{fg} \cdot \rho_v \cdot \rho_l}{(T_w - T_{sat}) \cdot \mu_{vf} \sqrt{\frac{\sigma}{\rho_l}}} \right\}^{1/4}$$

The boiling heat transfer coefficients and heat fluxes are plotted as a function of (T_w - T_{sat}) at ambient pressure (14.4 psia in the nacelle) according the the above correlation in Figure E-1 and E-2, respectively. Since the transition between these two regimes is unstable, we simply illustrate it by connecting (for each fluid) the point of maximum heat flux to that of minimum heat flux by a dashed straight curve (on the log-log plot). Note that the transition from nucleate to film regimes occurs at a different excess temperature for each fluid.

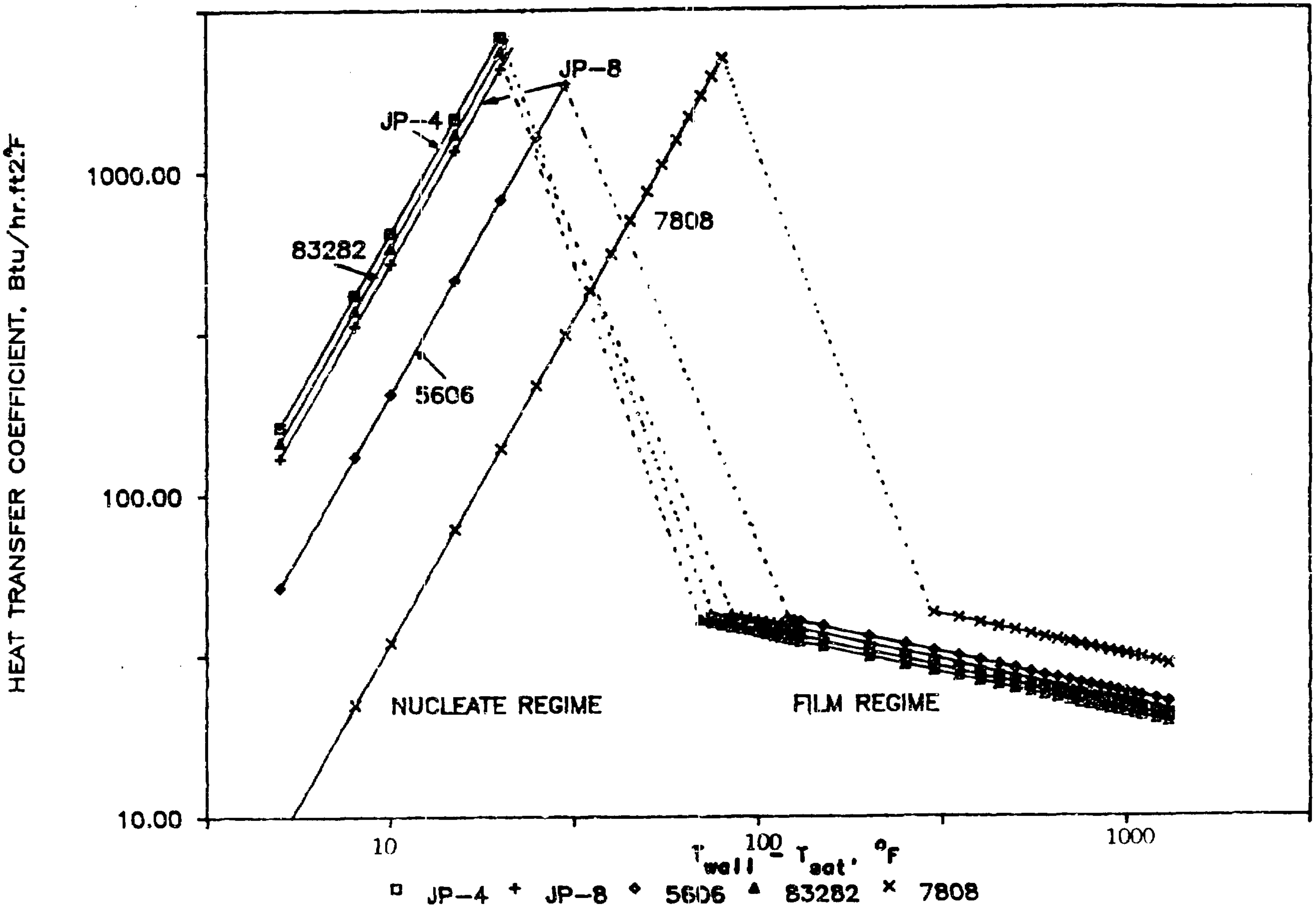


Figure E-1. Estimated Heat Transfer Coefficient; Boiling of Aircraft Fluids at 14.4 psia

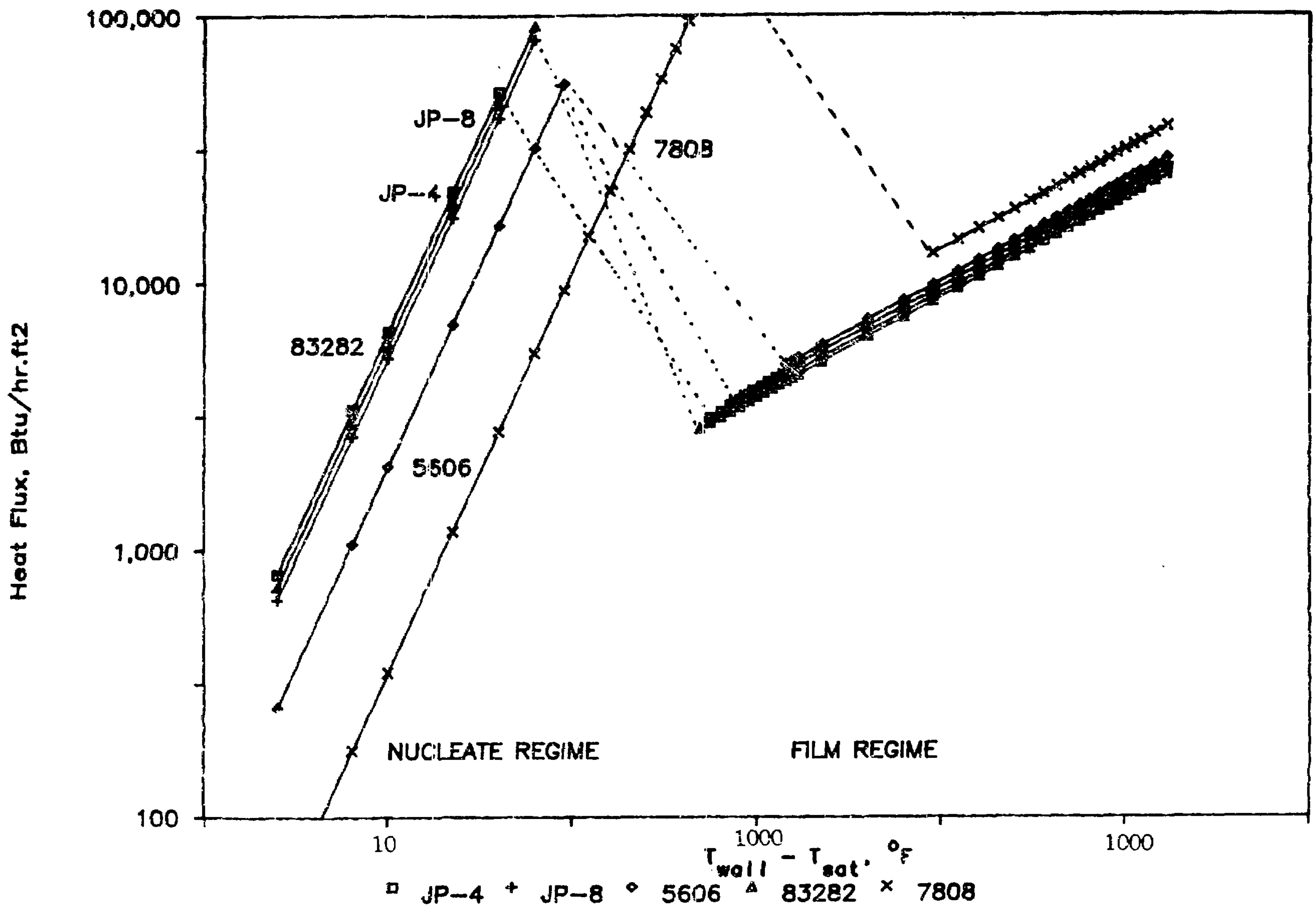


Figure E-2. Estimated Heat Flux; Boiling of Aircraft Fluids at 14.4 psia

Applicable Boiling Regime for Hot Surface Ignition Tests

It should be noted that the excess wall temperatures at which boiling changes from a nucleate to a film regime are functions of pressure according to the above equations. This is illustrated in Figs. E-3 to E-7 which show these excess temperatures as a function of pressure for the five fluids of interest. These plots delineate (by straight lines) the conditions at which the nucleate regime ends and the film regime begins.

In addition, in Figs. E-3 to E-7, we indicate as data points, the minimum excess temperature at which ignition was observed in this test program, i.e., (MHSIT - T_{sat}). Here, we assume that MHSIT is "similar" to the wall temperature (T_{wall}) measured in boiling-type studies. (This is not exact since the duct temperature may drop during the current test while T_{wall} can be maintained constant in boiling-type studies.) The data are for stream injection and for all tested ventilation air conditions. The pressure dependences of both MHSIT and T_{sat} are included in these data. Note that:

- all the JP-4 and JP-8 tests fall well into the film boiling regime. For these fluids, the required ignition temperature is high and the saturation temperature is low, yielding a large excess temperature.

- the 83282 tests may fall in either regime and are mostly in the nucleate regime. For this fluid, the required ignition temperature is low and the saturation temperature is high, yielding a small excess temperature. (It may even go negative, i.e., for this heavy fluid, the lighter ends might ignite while the heavier ends, remaining in the fluid, wet the duct surface.)

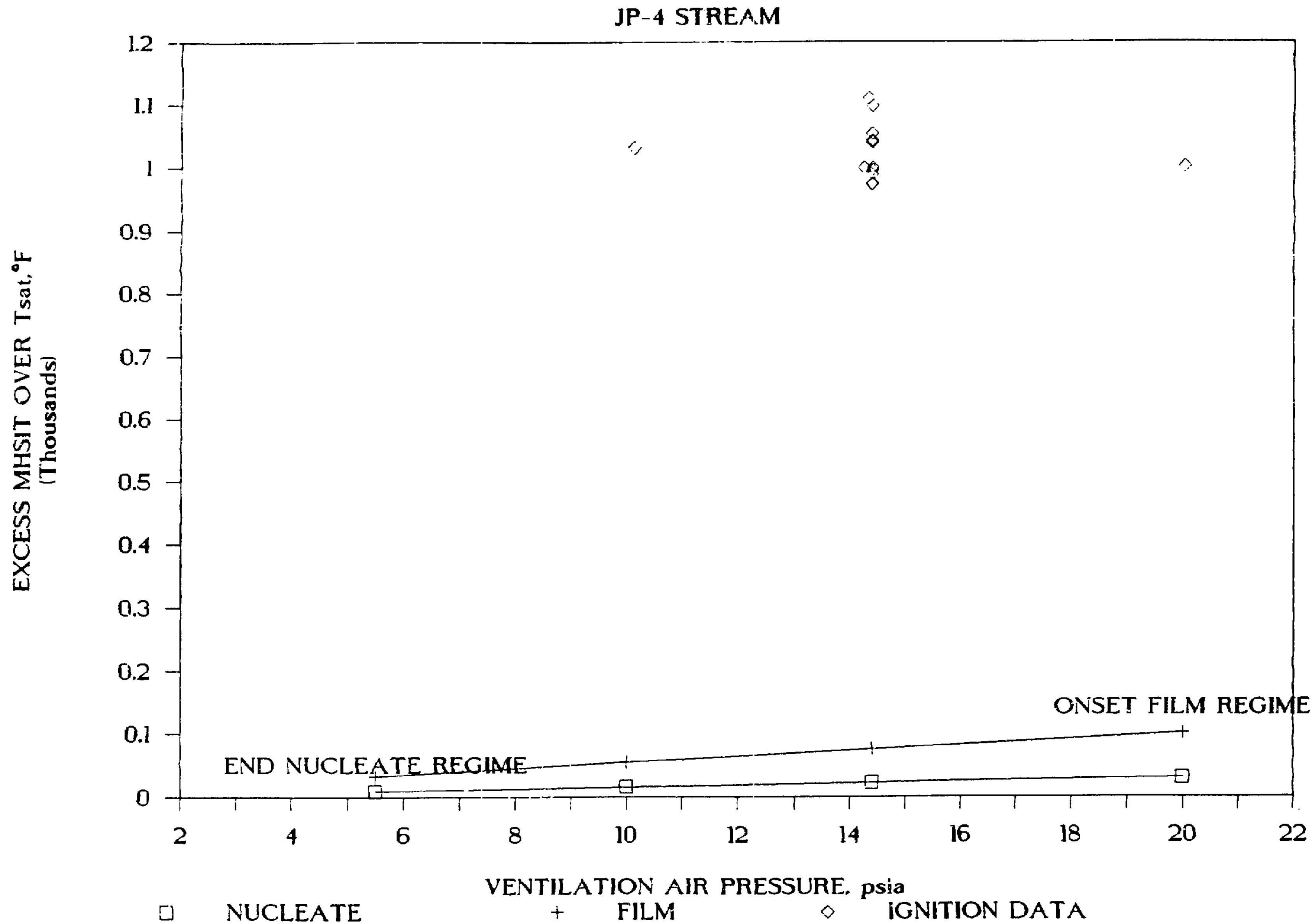


Figure E-3. Determination of Boiling Regime - JP-4 Stream

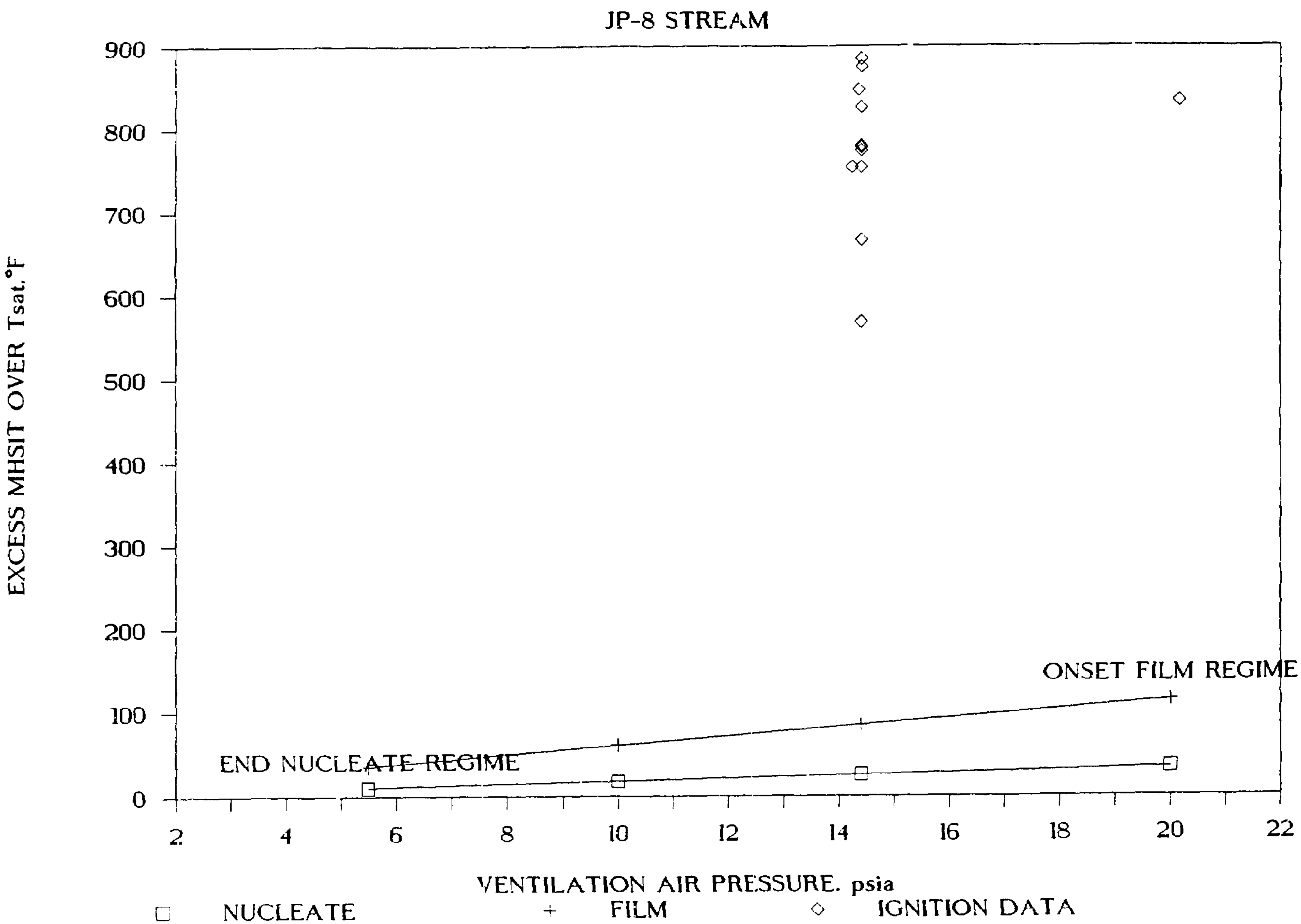


Figure E-4. Determination of Boiling Regime - JP-8 Stream

FIG E.5 DETERMINATION OF BOILING REGIME

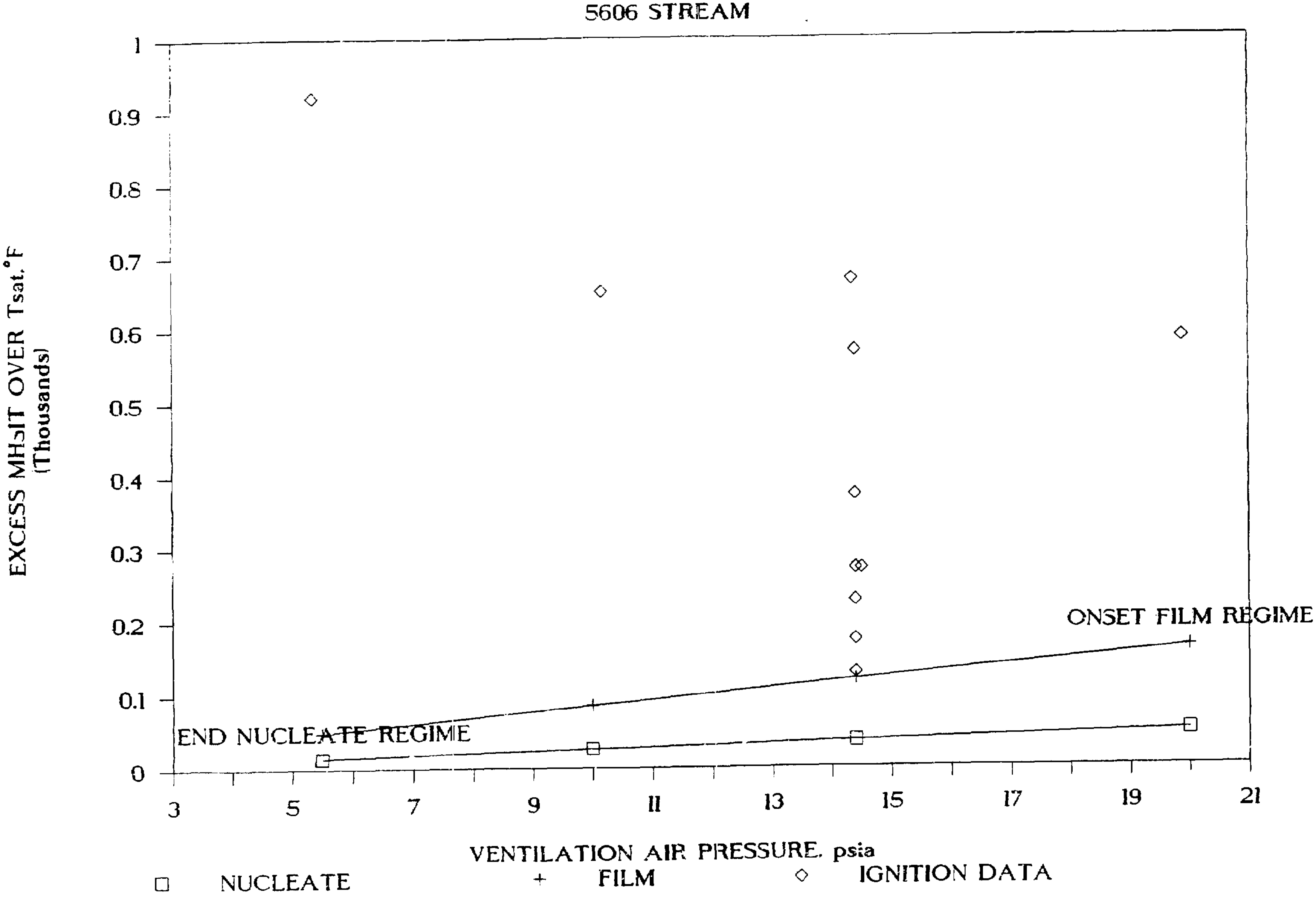


Figure E–5. Determination of Boiling Regime - 5606 Stream

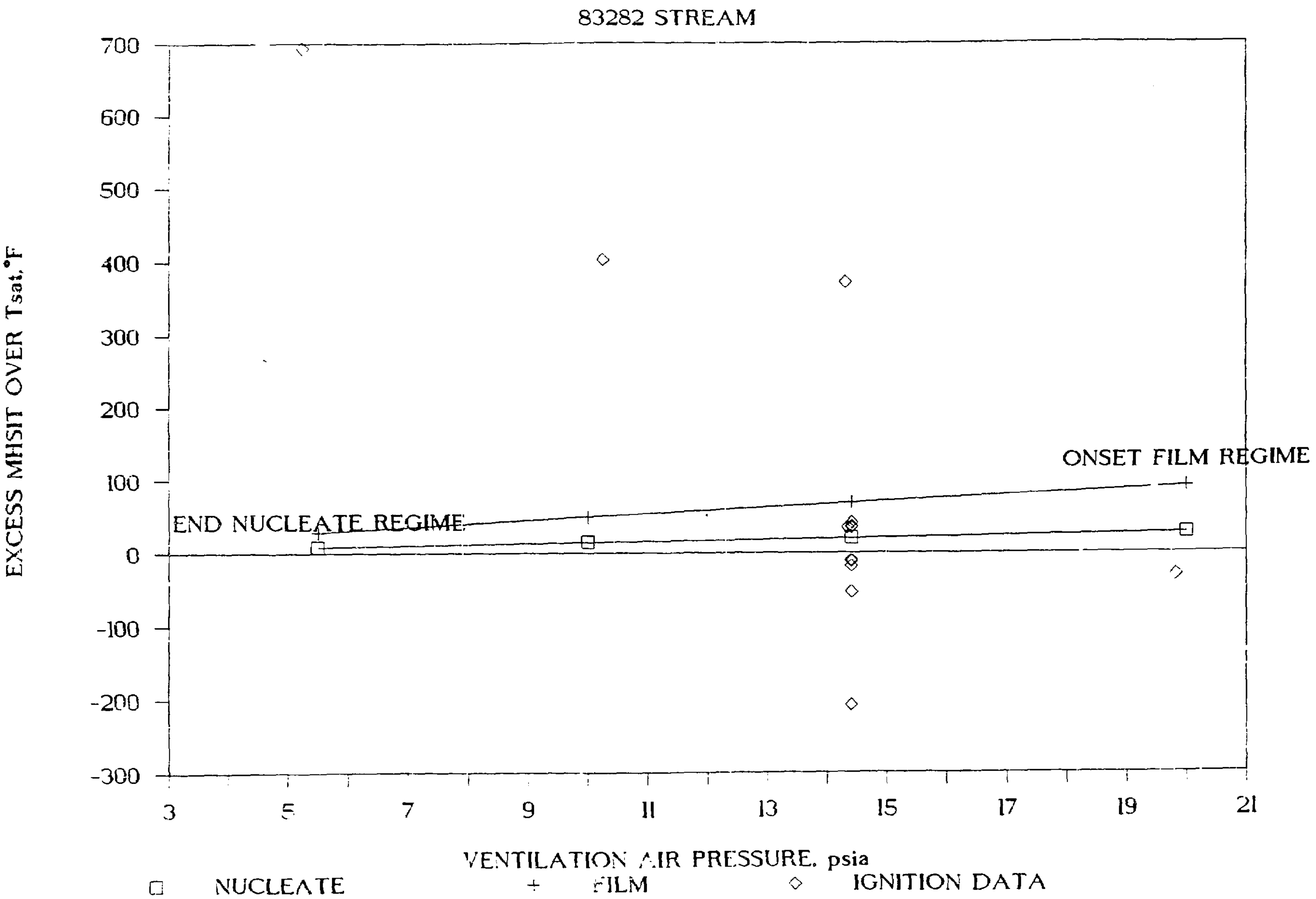


Figure E–6. Determination of Boiling Regime - 83282 Stream

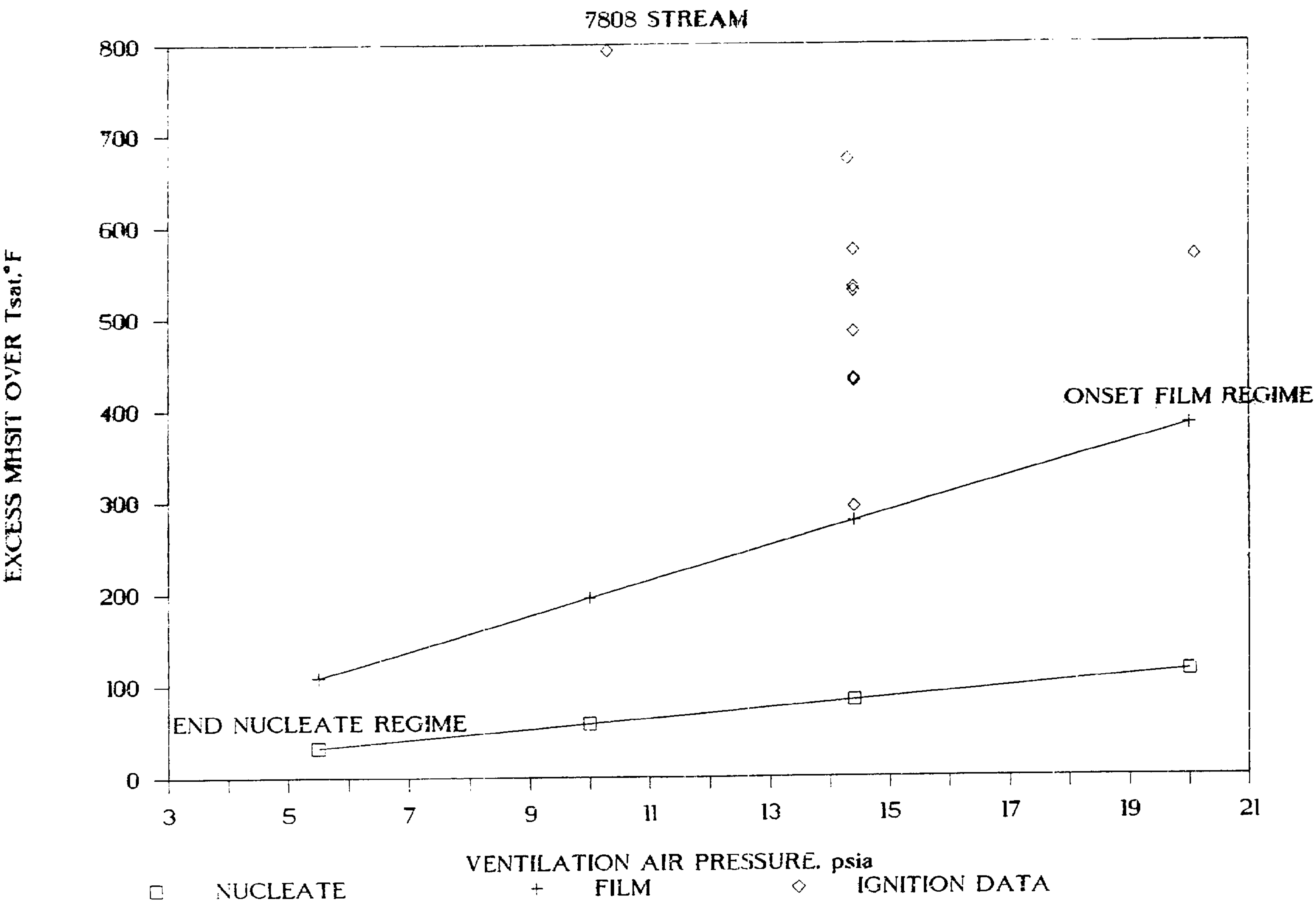


Figure E–7. Determination of Boiling Regime - 7808 Stream

- the 5606 and 7808 tests are intermediate between the above two behaviors, falling mainly in the film regime.

Overall Heat Transfer Coefficients

Figure E-1 indicates that the heat transfer coefficients are of the order of:

- 100 to 3000 Btu/hr·ft^{2}·°F for the nucleate boiling regime

- 20 to 40 Btu/hr·ft^{2}·°F the film boiling regime

Furthermore, as the excess temperature increases, h will increase in the nucleate boiling regime while it will decrease in the film boiling regime. However, the heat flux will increase in either case as shown in Figure E-2.

Also, note that the convective heat transfer coefficient from the hot air (inside the duct) to the duct wall (at 1 lb/sec) is about 200 Btu/hr·ft^{2}·°F. Since this convective heat transfer step is in series with the boiling step, the slower of the two will limit the overall heat transfer. In the case at hand, the overall heat transfer will be limited by the internal resistance on the air side for the case of nucleate boiling (for 83282); and by the external resistance on the vapor side for film boiling (for the other fluids).

Temperature of Bulk Fluid

As described previously, when the fluid stream impacts the duct, it spreads as a thin film outwardly from the impact point in all radial directions. After a very short distance, the spreading fluid breaks up into rivulets. This distance depends on a number of variables and is of the order of 0.3 inch based on photographs obtained in a similar experiment. It is reasonable to assume that most of the direct heat transfer (from duct to film) occurs in this small area (with a 0.3 inch radius).

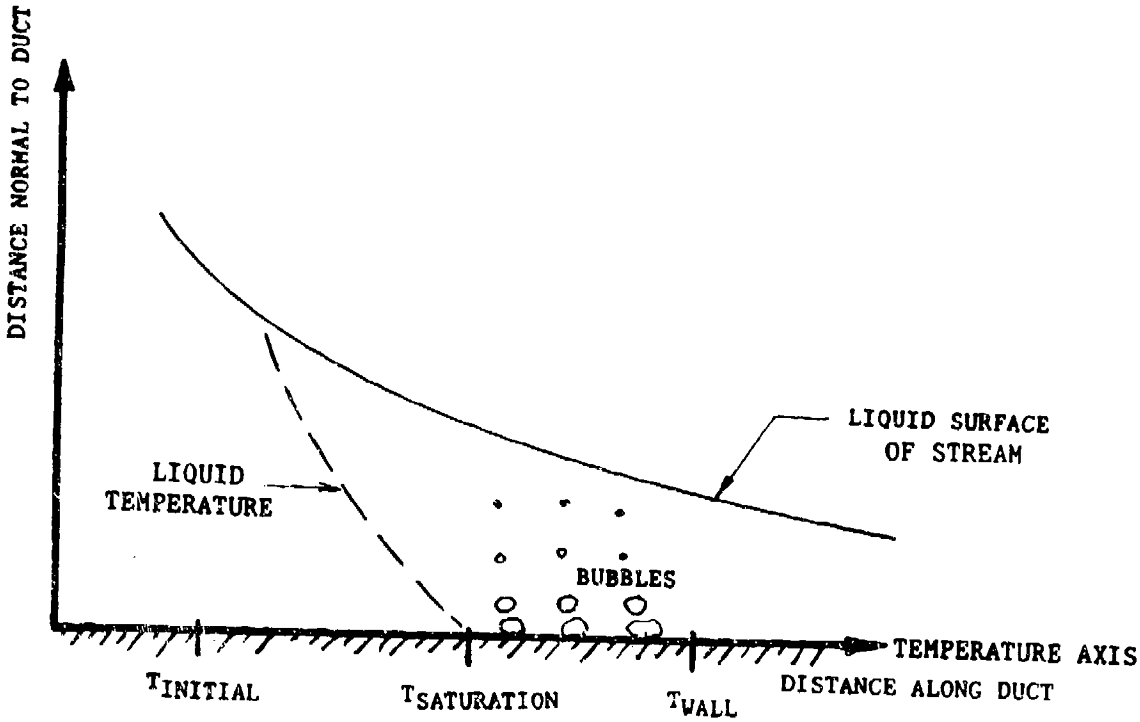
From an energy balance on this flowing stream, one predicts that bulk fluid temperature will not reach saturation near the duct surface. Even with the maximum possible overall heat transfer coefficient (200 Btu/hr·ft^2·^{o}F), the bulk temperature rises only to 160^{o}F due to the high fluid flow rate and the small contact area between the fluid and duct. In reality, a much lower h and temperature will be obtained because of the external thermal resistance in the film regime.

Thus, the bulk liquid temperature is much lower than its saturation temperature. In other words, boiling occurs in a subcooled regime, i.e., vapors are formed near the hot duct surface and rise through a cooler liquid where they condense releasing their latent heat.

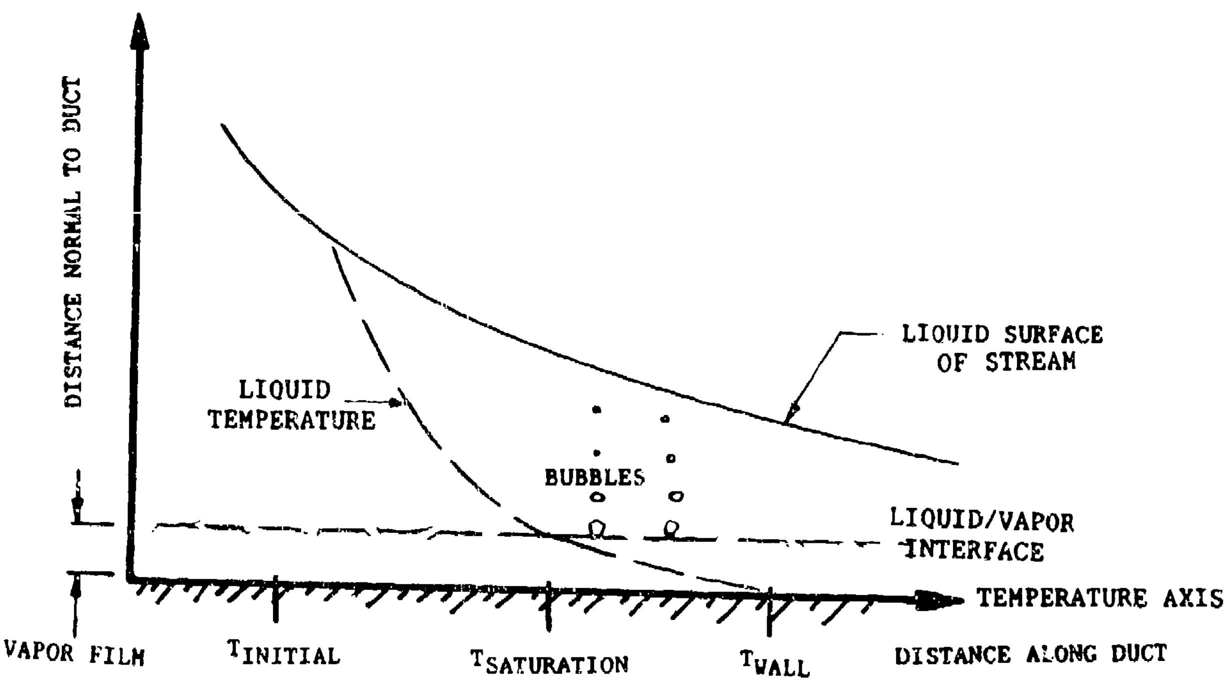
Physical Model of Hot Surface Boiling/Ignition

Based on the discussion above, one can develop the following picture for the case at hand, as illustrated in Fig. E-8. As the liquid flows over the hot plate, its temperature rises but the fluid remains subcooled. Vapors are formed only very near the surface where a very thin layer of fluid reaches the saturation temperature. The vapors rise through and condense in the liquid. The applicable regimes are mainly subcooled film boiling for all the fluids of interest except for 83202 where subcooled nucleate boiling also occurs.

At the edge of the spreading liquid film, the produced vapors exit the duct/liquid interface and are available for mixing with air and for ignition. A key parameter is the exit temperature of these vapors. This exit temperature can be modeled based on the physical description described above. Such a model is recommended for future work. As a rough approximation, we estimate that this exit temperature will be the arithmetic mean value between the temperature of the hot duct and the saturation temperature of the fluid. We suspect that the exit temperature may correlate with the autoignition temperature (AIT) of the fluids. Since we had no AIT data at various pressures, we could not test this correlation. Such work is recommended in the future.



(a) SUBCOOLED NUCLEATE BOILING



(b) SUBCOOLED FILM BOILING

NOTE: THE TEMPERATURE PROFILE IS ILLUSTRATED IN THESE DIAGRAMS (a & b) FOR A GIVEN LOCATION ALONG THE DUCT

Figure E-8. Boiling Regimes of Interest

Recommended Future Work

The discussions in Appendices D and E highlight the need for a basic study to elucidate the key processes involved in the ignition of aircraft fluids when in contact with a hot surface. Such a study may be carried out under the simplest conditions that are amenable to control and measurements. For example, experiments may consist of placing small droplets on a hot surface with a hypodermic needle. A flat surface would be used with a small depression at its center to stabilize the droplets. The test variables would include:

- o fuel type, droplet size and velocity
- o single v.s. multiple droplets
- o plate temperature from 100°C to 400°C over fluid boiling points
- o selected plate materials such as stainless steel and titanium

Measurements/observations (from video records) would include:

- o plate temperature as a function of time
- o droplet spreading behavior and size as function of time
- o location and time of ignition

Similar experiments can be conducted simulating a small stream instead of a spray. The results from such experiments would permit estimation of evaporation rates and heat transfer coefficients and identification of boiling regime under the range of conditions of interest. One can then use these results to interpret test data under more practicality conditions.

Reference

E-1 Rohsenow, W. M. and H. Y. Choi, "Heat, Mass and Momentum Transfer", Prentice-Hall, Edglewood Cliffs, N. J. 1961.

U.S. GOVERNEMNT PRINTING OFFICE: 1989-648-056